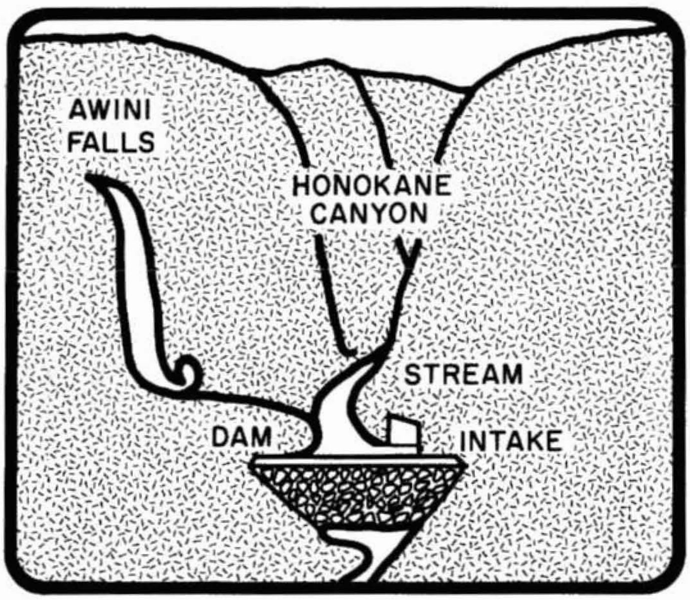
# KOHALA WATER RESOURCES MANAGEMENT AND DEVELOPMENT PLAN

## PHASE III

(FISCAL YEAR 1975)




REPORT PREPARED BY

Akinaka and Associates
Stephen P. Bowles
John F. Mink





September 1975

# KOHALA WATER RESOURCES MANAGEMENT AND DEVELOPMENT PLAN

## PHASE III

## FISCAL YEAR 1975

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September 1975

September 15, 1975

Mr. John Farias, Jr.
Chairman
Department of Agriculture
State of Hawaii
Honolulu, Hawaii

Dear Mr. Farias:

We are pleased to transmit our Phase III report for fiscal year 1975 of the Kohala Water Resource Management and Development Plan. In preparing this report we have paid particular attention to the problems of maintaining and operating the Kohala Ditch effectively with respect to supply and demand.

The 900 foot horizontal drill hole and the computer model developed for management analysis represent firsts for the State of Hawaii and we are proud to have assisted the Task Force in these accomplishments. We feel that the information contained in this report will materially aid the Task Force in its efforts at Kohala.

Sincerely,

Arthur Y. Akinaka
ARTHUR Y. AKINAKA

Stephen P. Bowles
STEPHEN P. BOWLES

Robert Y. Akinaka
ROBERT Y. AKINAKA

John F. Mink
JOHN F. MINK

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# INTRODUCTION

Phase III of the Kohala Water Resources Management and Development Plan was initiated during fiscal year 1975. As described in the Phase II report, this phase is intended to span the implementation of specific projects and activities related to the establishment of an expanding irrigation water program. The primary objective of the first year of Phase III has been the systematic evaluation of the Kohala Ditch between Pololu and the point of origin at Waikaloa stream. Activities consisted of:

1. Detailed field evaluation and description of tunnels, intakes and flumes.
2. Detailed hydrologic analysis of flows to the ditch.
3. Exploration drilling for high level groundwater in Honokane Nui valley.

During the course of investigations, it became evident that analyses of the ditch system as related to flows, improvements and demand were difficult to interpret. A computer model was developed to compare supply and demand thus permitting rapid evaluation of flows. This model was particularly helpful in evaluating the effectiveness of the Awini section of the ditch and establishing the impact of storage on maintaining various levels of low flow.

With the submission of this report, the Task Force should be well equipped to pursue the orderly change of water useage from sugar to diversified agriculture.

## RECOMMENDATIONS FOR FISCAL YEAR 1976

With the submission of this report plus the comprehensive Phase II report, the Kohala Task Force has access to a thorough analysis of the situation facing the future of agricultural water for Kohala. Future activities must be devoted to the integration of demand to the deliveries from, and the operation of, the Kohala Ditch. The management model developed during the past year should be used effectively in the ditch operations and agricultural operations. While storage is not urgently needed at this time, a continued exploratory drilling program is needed in upper Honokane Nui canyon in order to locate adequate high level dike storage to facilitate the anticipated reestablishment of large scale irrigation in Kohala. Surface storage should be evaluated and integrated into the system where feasible.

Present water demand, and the foreseeable growth of that demand, warrant a serious look at the future operation of the Awini section of the Kohala Ditch. Model analyses, incorporated in this report, seriously question the value of a substantial portion of the Awini section, particularly in view of the presently committed agricultural activities. It should be recognized that the Awini section should <u>not</u> be abandoned but serious consideration should be given to "mothballing" the portion from Honopue to Waikaloa.

The Kohala Water Resource Management and Development Plan was created as a dynamic action program to permit economic flexibility. Future water activities and programs undertaken by the Task Force should be planned and instituted with the best knowledge available at the time. The Task Force must not permit the Water Plan to slip in relation to its other responsibilities in North Kohala. To this end, the consulting team recommends the following program for the fiscal year 1976:

1. First 6 months

   A. Irrigation Demand (Both present and planned)

      1) Review and integrate projected demand into computer model(s) and revise forecast of supply accordingly.

      2) Prepare (Based on above forecasts)

         a) Plan for useage of Awini section (To include possible "mothballing")

         b) Economic analysis and plan of operations of Kohala Ditch on a year by year projection of supply vs demand

      3) Prepare detailed analysis and plan for useage of and improvements to the primary distribution system from the ditch to the user.

   B. Kohala Ditch Company

Prepare a detailed evaluation of Ditch Company with respect to ownership, management and maintenance as recommended in Phase II report.

C. Exploration Program

1) Prepare detailed plans for trail improvement in upper Honokane Valley.

2) Select site(s) for additional horizontal drill hole(s).

3) Select site for temporary base camp for trail construction and drilling activity.

4) Prepare specifications for trail construction and drilling.

5) Let bids.

2. Second 6 months

A. Exploration program

1) Commence trail improvements in upper Honokane Nui

2) Commence drilling (may overlap into FY 1977).

B. Kohala Ditch

1) Commence changes to Awini section

2) Design improvements to intake dam in Honokane Nui

3) Commence improvements to ditch and primary transmission (Niulii to Puakea)

In order for the Task Force to maintain an orderly progression of the Water Plan it will be necessary to have all water related activities closely coordinated with other decisions of the Task Forces such as new agricultural enterprises, increasing demand of existing business, projected layoffs, etc. It is recommended that the Task Force be particularly cognizant of such coordination and progression in water planning.

## EXPLORATORY DRILLING

<u>Preparation of Contract Plans and Specifications and Administrative procedures for exploratory drilling in Honokane Nui Valley (East Branch)</u>

On August 1, 1974, work was commenced on the preparation of contract plans and specifications for exploratory drilling. The plans and specifications were based on the present methods of drilling and currently available equipment. Contract plans and specifications are on file at the Department of Land and Natural Resources and the Department of Agriculture.

Advertising of bids for subject project commenced on August 17, 1974 and bids were opened on September 3, 1974. Continental Drilling Company was the sole bidder with the following bid:

| | |
|---|---|
| Basic Bid (General Work and Exploratory Horizontal Test Hole - Location 1, Site A) | $40,808.00 |
| Alternate "A" Bid (Communication System) | 5,230.00 |
| Alternate "B" Bid (Exploratory Horizontal Test Hole - Location 1, Site B) | 15,140.50 |
| Alternate "C" Bid (Exploratory Vertical Test Holes - Location 2 and/or Location 2 and/or Location 3 | 15,473.25 |

Based on the above bid, the Kohala Task Force awarded the Contract to Continental Drilling. Notice to Proceed dated October 15, 1974 was issued to Continental Drilling for work on Basic Bid and Alternate "A".

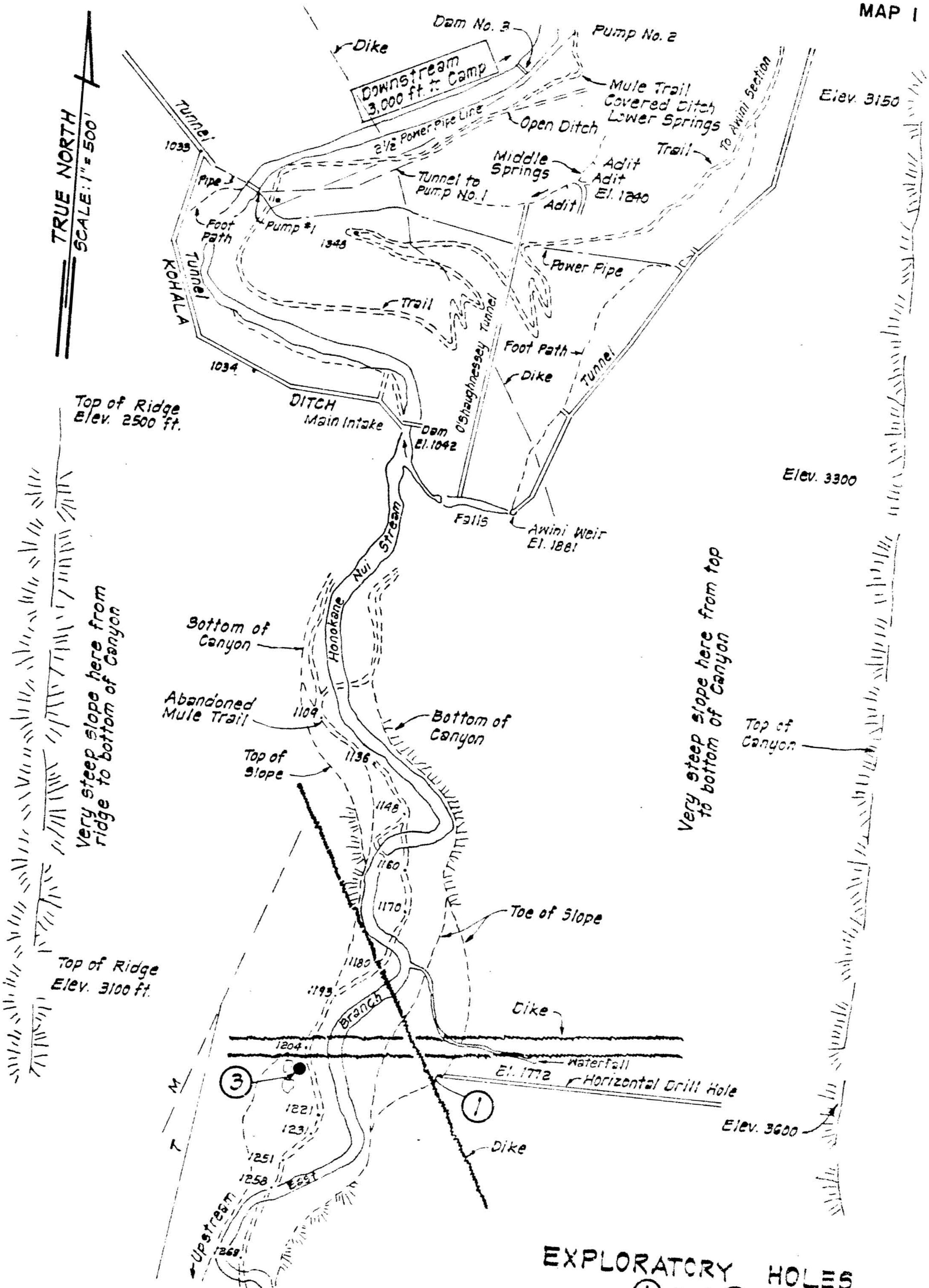
Stephen P. Bowles and Akinaka & Associates, Ltd. provided weekly to bi-monthly project inspections during the progress of the work, reviewed and recommended approval for all progress payment requests by the Contractor, reported on the progress of the work by quarterly progress reports, and based on the hydrologic and geologic findings, recommended additional exploratory work.

Work was completed on the exploratory drilling on July 14, 1975. The total cost of the 900 foot deep horizontal exploratory hole and 300 foot deep vertical exploratory hole was $77,571.20.

Horizontal Drill Hole

As recommended in the Phase II study, a horizontal drill hole was constructed in order to explore for a suspected high level dike compartment behind Sproat Falls. The location of the drill hole is shown in Map 1. A large trachyte dike of the Hawi volcanic series crosses Honokane Nui below the diversion dam for pump #1, disappears into the pali beneath the Awini penstock and reappears in the cliff face by Awini Falls. Various projections of this dike implied that the dike might continue up the valley within the pali and nearly parallel to the cliff face.

Because of the perennial and constant discharge of springs some 500 feet above the canyon floor supplying Sproat Falls, it was suspected that these springs might represent




EXPLORATORY HOLES
1 and 3
HONOKANE NUI CANYON
HONOKANE, NO. KOHALA, HAWAII

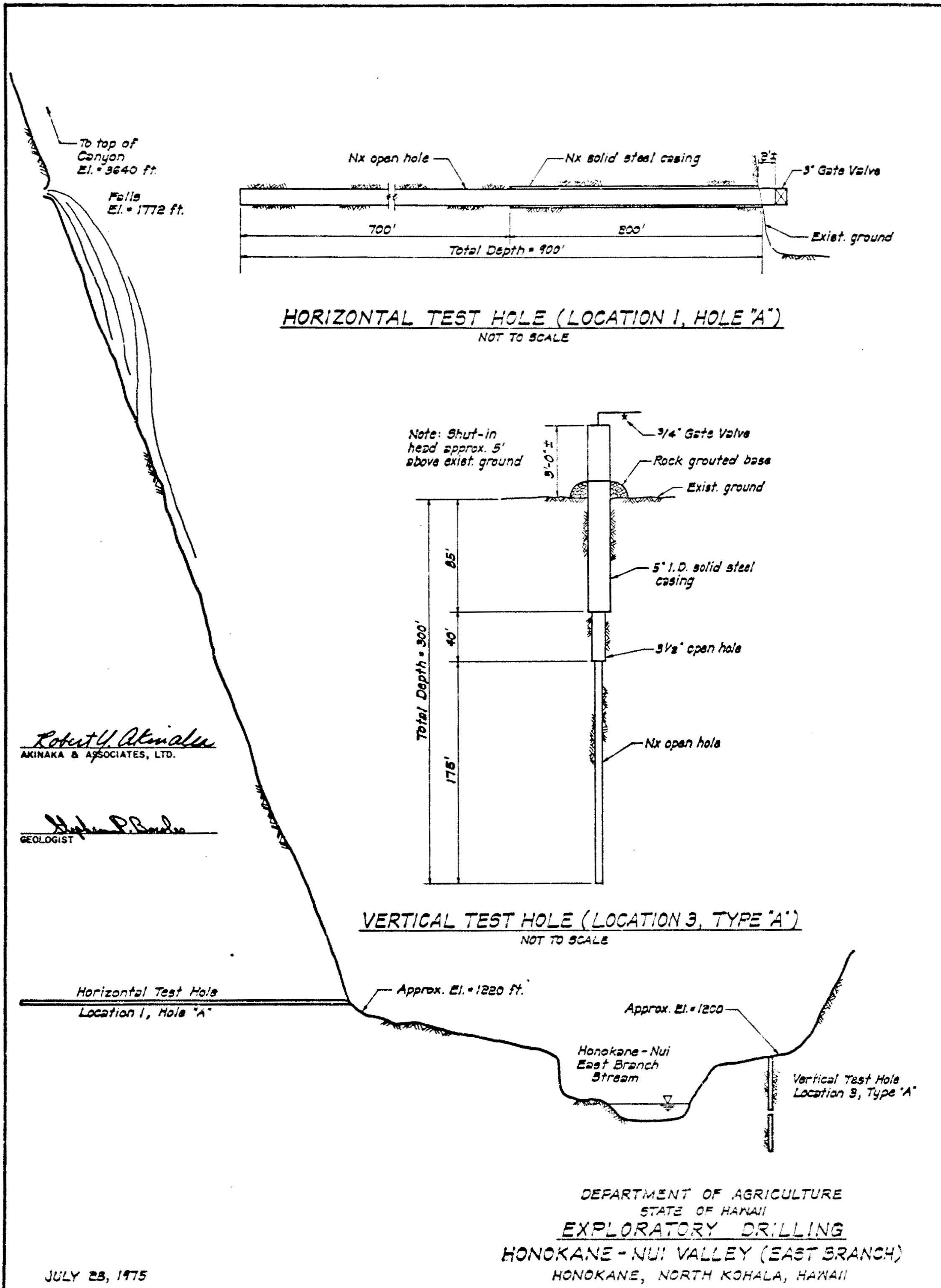
REFERENCE: KOHALA CORP. MAPS

overflow from a major storage compartment within the pali and confined by the trachyte dike. The purpose of the drill hole was to determine whether such a compartment could be located and developed within reasonable economic constraints. A horizontal drill hole up to 1000 feet in length was relatively inexpensive when compared with an exploratory tunnel and much simpler to accomplish.

Details of the construction are contained elsewhere in this report and also within progress reports filed during the course of construction. The hole was successfully drilled to a depth of 900 feet and represented the first major attempt at horizontal drilling in Hawaii. No significant water flow was encountered and there was no evidence of dikes or faults either in the drillers reports or in the core samples which were taken continuously during drilling. Several minor ash beds were intersected during the drilling, however, the major rocks were pahoehoe lavas which had a high porosity and were thin bedded. Such lavas are typical of the lavas found in Honokane Nui valley.

The drill hole demonstrated that, if the trachyte dike compartmentalizes significant high level storage, such storage is located deep within the canyon face and the exploration and development of such storage would represent a relatively expensive and high risk undertaking.

Figure A is a detailed drawing of the horizontal hole as constructed. The hole was closed off with a discarded


To top of Canyon El. = 3640 ft.
Falls El. = 1772 ft.
Nx open hole
Nx solid steel casing
2'±
3" Gate Valve
700'
200'
Total Depth = 900'
Exist. ground
HORIZONTAL TEST HOLE (LOCATION 1, HOLE "A")
NOT TO SCALE
Note: Shut-in head approx. 5' above exist. ground
3/4" Gate Valve
Rock grouted base
Exist. ground
3'-0" ±
85'
40'
175'
Total Depth = 300'
5" I.D. solid steel casing
3½" open hole
Nx open hole
VERTICAL TEST HOLE (LOCATION 3, TYPE "A")
NOT TO SCALE
AKINAKA & ASSOCIATES, LTD.
GEOLOGIST
Horizontal Test Hole
Location 1, Hole "A"
Approx. El. = 1220 ft.
Approx. El. = 1200
Honokane - Nui East Branch Stream
Vertical Test Hole Location 3, Type "A"
DEPARTMENT OF AGRICULTURE
STATE OF HAWAII
EXPLORATORY DRILLING
HONOKANE - NUI VALLEY (EAST BRANCH)
HONOKANE, NORTH KOHALA, HAWAII
JULY 23, 1975

AS-BUILT

valve should it ever be deemed appropriate to reenter and drill the hole deeper. Directional surveys were taken every 50 feet during construction and this data is listed in Table a.

Vertical Test Hole

Following completion of the horizontal drilling, the exploratory activity shifted across the valley to the site marked in Map 1. The purpose of this vertical hole was to determine the characteristics of the high level dike compartments situated immediately beneath the valley floor. Preliminary field investigations indicated that high level groundwater was moving towards Honokane Nui stream and discharging into the stream. Evidence of minor springs and seeps located just upstream of the two parallel dikes which disappear in the pali face at Sproat Falls (Map 1) seemed to be clear evidence that the compartment was saturated up to and probably above the stream level.

The vertical hole was designed to determine:

1. the type of aquifer material
2. the water levels encountered during drilling
3. the yield of the aquifer

Also considered was the potential of drilling production wells for pumping stored water into the stream during dry weather as a means of augmenting ditch flow.

Aquifer material consisted of thin bedded pahoehoe lavas with a high porosity and moderate permeability. Several

DIRECTIONAL SURVEY FOR DETERMINING
THE INCLINATION AND DIRECTION OF THE EXPLORATORY
HORIZONTAL DRILL HOLE USING THE FAJARI
BORE - HOLE SURVEYING INSTRUMENT
Location 1, Site A (HOLE "A")

| Depth of Hole Survey Taken (Ft) | Inclination | Direction | Date Survey Taken |
|---|---|---|---|
| 0 | 2° Up | N 86° E | Oct. 22, 1974 |
| 50 | 3° Up | S 94° E | Oct. 23, 1974 |
| 100 | 3° Up | S 104° E | Oct. 25, 1974 |
| 150 | 2° Up | S 96° E | Oct. 28, 1974 |
| 150 | Reading No Good | Reading No Good | Nov. 11, 1974 |
| 150 | 3° Down | S 90° E | Nov. 13, 1974 |
| 200 | 3° Down | S 90° E | Nov. 15, 1974 |
| 250 | 4° Down | S 95° E | Nov. 22, 1974 |
| 300 | 3° Down | S 93° E | Nov. 22, 1974 |
| 400 | 3° Up | S 93° E | Dec. 6, 1974 |
| 450 | 2° Up | S 94° E | March 25, 1975 |
| 500 | 1° Up | S 94½° E | March 26, 1975 |
| 550 | 1° Up | S 94½° E | March 27, 1975 |
| 600 | 1° Up | S 95° E | March 27, 1975 |
| 650 | 1° Up | S 95° E | March 27, 1975 |
| 700 | 1° Up | S 95° E | March 27, 1975 |
| 750 | 1° Up | S 95° E | March 28, 1975 |
| 800 | Level | S 94° E | March 29, 1975 |
| 850 | 1° Down | S 95° E | March 31, 1975 |
| 900 | 1° Down | S 94° E | April 1, 1975 |

TABLE a

thin ash beds were encountered but were of little hydrologic significance. Weathering of the bedrock extended to 20 or 30 feet below the ground surface. Cores were taken continuously although the brittle porous pahoehoe caused relatively poor core recovery.

The initial water level was about 1 foot below ground surface. A permanent 5 inch casing was set at 80 feet followed by a temporary NW casing set to a depth of 125 feet. NX open hole was drilled to a depth of 300 feet. The water level, taken by shutting in the NW casing, was about five feet above the ground surface. The NW casing was subsequently pulled and the 5 inch casing was shut in resulting in a duplication of water level taken with the NW casing in place. When allowed to free flow the discharge was measured at 2.5 gpm.

A series of pumping tests were run. Test results indicated that wells with yields of up to 700 gpm (1 mgd) could be constructed. A controlled aquifer test was performed to determine coefficients of yield and storage for further feasibility evaluations. Table 6 lists the data collected from the aquifer test. Interpretation of the results is contained later in the report.

Figure A shows the as built dimensions of the well. Appropriate stone work and valving were installed to protect the well and permit further testing should it be necessary.

While the exploration work during Phase III activities has provided clarification of the high level groundwater

# WATER LEVEL IN VERTICAL EXPLORATORY DRILL HOLE
## LOCATION 3, TYPE "A" HOLE
## DURING AQUIFER TEST
## JULY 11, 1975

| TIME SINCE PUMPING BEGAN (MIN.) | DRAWDOWN (FT.-IN.) WATER LEVEL TO TOP OF CASING | TIME TO FILL 55 GAL. DRUM (SEC.) |
|---|---|---|
| 0 | 0 | |
| 1 | 4' - 4" | |
| 2 | 5' - 7" | |
| 3 | 5' - 9½" | |
| 4 | 6' - 5 3/4" | |
| 5 | 6' - 11½" | |
| 6 | 7' - 2" | |
| 7 | 7' - 4½" | |
| 8 | 8' - 2 3/4" | |
| 9 | 9' - 0" | |
| 10 | 8' - 11" | 48.5 |
| 16 | 10' - 3½" | |
| 20 | 11' - 0" | 48.2 |
| 25 | 11' - 10" | |
| 30 | 12' - 3½" | 48.0 |
| 40 | 13' - 4" | 49.2 |
| 50 | 14' - 5" | 50.0 |
| 60 | 15' - 2" | 49.5 |
| 70 | 15' - 9" | 48.6 |
| 80 | 16' - 1" | 49.4 |

REMARKS

PRESENT: Continental Drilling Co.
Darryl McCleery
Henry Featheran
Pua Raymond

Akinaka & Associates, Ltd.
Robert Y. Akinaka

WEATHER: Early morning cloudy
Rest of day - clear and sunny

PUMP: Berkeley Submersible Pump (See Enclosed Pump Brochure)
1) Discharge pipe - 2½" I.D. w/2" Gate Valve
2) Pump setting @ 60' below top of 5" I.D. casing (Bottom of 5" I.D. casing @ 85')

MEASURING INSTRUMENTS:
1) Wire Conductor Type Water Level Indicator and 12 Ft. Tape
2) Stop Watch (1/5 second)
3) 55 Gallon Drum

PUMP TEST BEGAN @ 7:05 A.M.

NOTE: First 10 Drawdown Readings (First 10 minutes) was Measured By Wire Conductor Water Level Indicator and By 12 Ft. Tape Measure.

WATER LEVEL IN VERTICAL EXPLORATORY DRILL HOLE
LOCATION 3. TYPE "A" HOLE
DURING AQUIFER TEST
JULY 11, 1975

| TIME SINCE PUMPING BEGAN (MIN.) | DRAWDOWN (FT.-IN.) WATER LEVEL TO TOP OF CASING | TIME TO FILL 55 GAL. DRUM (SEC.) | REMARKS |
|---|---|---|---|
| 90 | 16' - 9" | 49.0 | |
| 100 | 17' - 0" | 48.6 | |
| 110 | 17' - 5" | 48.0 | |
| 120 | 17' - 8" | 47.0 | |
| 130 | 17' - 10½" | 47.0 | |
| 140 | 18' - 1½" | 47.5 | |
| 150 | 18' - 1½" | 47.2 | |
| 160 | 18' - 3" | 47.2 | |
| 170 | 18' - 6½" | 47.5 | |
| 180 | 18' - 6½" | 47.8 | |
| 190 | 18' - 5" | 48.5 | |
| 200 | 18' - 3" | 48.8 | |
| 210 | 18' - 3" | 49.2 | |
| 220 | 18' - 2" | 49.0 | |
| 230 | 18' - 5½" | 49.2 | |
| 240 | 18' - 3" | 49.0 | |
| | AVE. = | 48.4 SEC. | |
| | AVE. = | 68.2 GPM | |

WATER LEVEL IN VERTICAL EXPLORATORY DRILL HOLE
LOCATION 3, TYPE "A" HOLE
DURING AQUIFER TEST
JULY 11, 1975

| TIME RECOVERY BEGAN (MIN.) | RECOVERY (FT.-IN.) WATER LEVEL TO TOP OF CASING | REMARKS |
|---|---|---|
| 0 | 18' - 3" | RECOVERY TEST BEGAN AT APPROXIMATELY 11:05 A.M. |
| 1 | 13' - 0" | |
| 2 | 12' - ½" | |
| 3 | 11' - 2" | |
| 4 | 10' - 10" | |
| 5 | 10' - 3½" | |
| 6 | 9' - 11" | |
| 7 | 9' - 6" | |
| 8 | 9' - 1" | |
| 9 | 8' - 9" | |
| 10 | 8' - 5½" | |
| 15 | 7' - 0" | |
| 20 | 5' - 9" | |
| 25 | 4' - 9½" | |
| 30 | 3' - 10" | |
| 40 | 2' - 8" | |
| 50 | 1' - 8" | |
| 60 | 0' - 11" | |
| 70 | 0' - 4¼" | |
| 77 | 0' - ½" | |
| 79 | 0' - 0" | FULL RECOVERY |



TABLE b

storage in Honokane Nui, more exploratory mapping and drilling is needed farther up the valley. No work was conducted on the Koelling Tunnel as the trails were found to be unsafe without added improvements. Horizontal drilling in the valley floor below the tunnel remains a distinct possibility for storage release particularly as a result of the successful drilling during this stage of work.

EXPLORATORY HORIZONTAL DRILLING
(LOCATION 1, HOLE "A")

DRILL SITE

70 GPM PUMP TEST DISCHARGE

5" FLOWING EXPORATORY WELL

COMPLETED HOLE WITH
APPURTENANCES

EXPLORATORY VERTICAL DRILLING
(LOCATION 3, HOLE TYPE "A")

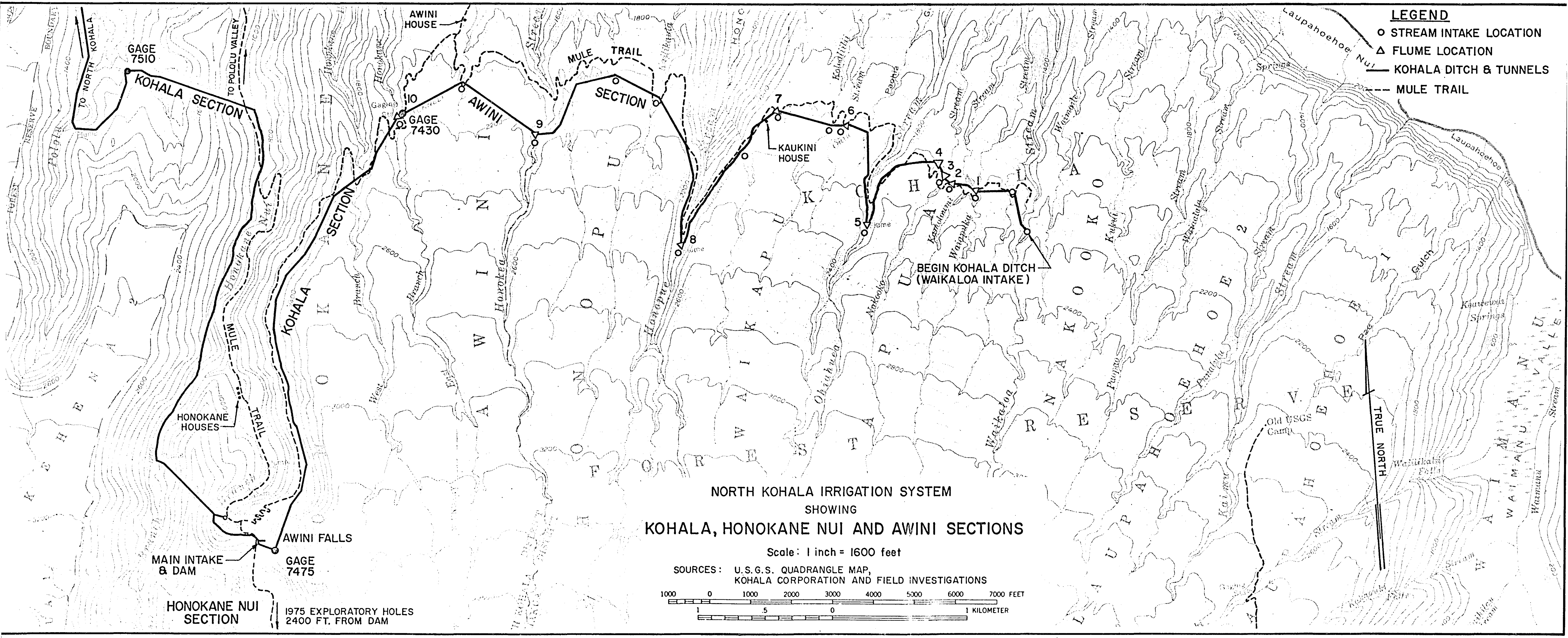
## PRESENT CONDITION OF EXISTING STRUCTURES IN THE AWINI SECTION

A three day field trip was made (February 19 - 21, 1975) to document and evaluate structures and facilities in Awini section of the Kohala Ditch. The field trip was made possible by the Kohala Ditch Company. The route of the field trip by mules was along the makai trail (Pololu-Honokane Nui-Honokane Iki) to the Awini Ditchmen's house, thence along the mule trail which follows the ditch system to its source, the Waikaloa intakes. (See Map 2)

Existing structures were identified during the field trip. The transmission system consists of intakes, tunnels, flumes, and adits. In addition, the supporting structures include (1) mules trails, (2) foot trails to transmission structures, and (3) Ditchmen's houses.

### Intakes

Deductions concerning flows from the Awini Section are based on the 1928-60 record, a period when the system was presumably maintained in the best achievable state. But even under optimum maintenance, alluvium and trash accumulate in the collection pools behind the small retaining dams, at the intake, and in the tunnels after heavy rains. To keep the collection and transmission system in efficient working order a great deal of maintenance has to be practiced. Without it the collection pools fill to the rim with bed load alluvium causing the moderate and even some low flows to escape. The alluvium reduces the open cross-section of the intakes, trash collects against the grating, and debris


LEGEND
o STREAM INTAKE LOCATION
△ FLUME LOCATION
KOHALA DITCH & TUNNELS
MULE TRAIL
NORTH KOHALA IRRIGATION SYSTEM
SHOWING
KOHALA, HONOKANE NUI AND AWINI SECTIONS
Scale: 1 inch = 1600 feet
SOURCES: U.S.G.S. QUADRANGLE MAP,
KOHALA CORPORATION AND FIELD INVESTIGATIONS
1000 0 1000 2000 3000 4000 5000 6000 7000 FEET
1 .5 0 1 KILOMETER
GAGE 7510
KOHALA SECTION
TO NORTH KOHALA
TO POLOLU VALLEY
AWINI HOUSE
GAGE 7430
AWINI SECTION
MULE TRAIL
KAUKINI HOUSE
BEGIN KOHALA DITCH (WAIKALOA INTAKE)
KOHALA SECTION
HONOKANE HOUSES
MULE TRAIL
AWINI FALLS
MAIN INTAKE & DAM
GAGE 7475
HONOKANE NUI SECTION
1975 EXPLORATORY HOLES 2400 FT. FROM DAM
TRUE NORTH
Old USGS Camp
Laupahoehoe Nui
KOHALA FOREST RESERVE
PUU O UMI NATURAL AREA RESERVE

passes into the tunnels and flumes, reducing their carrying capacities. All of these conditions prevail today, now that attention to the sector has waned. (See photos of intake structures).

The transmission tunnel lies at an elevation where the slope of the streams change from moderate to steep. The stream channels are cut directly into bedrock and under natural conditions erosional debris can find no stable resting sites, but when a deep pool is created by constructing a small artificial dam, a fairly stable alluvial trap forms. Once in the trap the alluvium, normally composed of the size range sand to boulders, must be removed by maintenance crews. However, it may be possible to retard deposition of alluvium behind the dams by constructing sediment traps upstream. Eventually these too would have to be cleaned, but for long intervals more flows would be diverted to the intakes and the tunnels, and the tunnels and flumes would be able to run full.

The intakes were designed for small streams so that when their basal portions are jammed with alluvium they probably cannot accept much more than the low flows. The normal intake instructure consists of a rectangular frame 0.5 to 1 foot high and 1.5 to 2 feet wide holding several strong vertical iron bars. The largest intake structure seen during field observation is on Kailikaula Stream where the rectangular frame is 3 by 3 feet, capable of accepting a flow of 31 MGD under a 1 ft. drop in head. On Waikaloa

Stream the frame is also large, 4 by 1.5 feet, capable of taking 24 MGD. Through many of the intakes less than 5 MGD will flow under a one foot head differential. The intakes are therefore a serious constraint on the amount of water the system could collect.

Intake dimensions were measured where accessible during the field inspection, and theoretical collection capacities were computed. The capacities and the fraction of flows, as derived from volume duration curves, they are able to include are as follows (includes only those intakes whose dimensions were measured):

| Stream | Intake Capacity (MGD) | % Flow Contributed by Q = Capacity |
|---|---|---|
| Waikaloa R. Br. | 24 | 65% |
| Waikaloa L. Br. | 3 | 55 |
| Waiapuka | 11 | 75 |
| Kamoloumi | 11 | 90 |
| Nakookoo R. Br. | 5 | 45 |
| Oniu | 7 | 80 |
| Honopue 2nd R. Br. | 2 | 85 |
| Kailikaula | 31 | 85 |
| Honokea 2nd R. Br. | 7 | 70 |
| Honokea L. Br. | 6 | 30 |
| Waipuhi | 2 | 40 |
| Honokane Iki E. Br. | 12 | 60 |

The comparisons are rough because of the approximate nature of the calculations, but nevertheless they indicate the constraint the intakes impose on collected flow. Some streams, such as Kamaloumi, 2nd R. Br. Honopue, Oniu and Kailikaula, have quite effective intake dimensions, while others, especially the L. Br. Honokea, which is the main stem of the stream, are not efficient collectors for the volume of available water. Should the Awini Sector be continued, many of the intakes must be redesigned and re-built.

Tunnels

The tunnels are in reasonably good condition, but alluvium has been accumulating in recent years because sluicing to keep the floor free of debris has been discontinued. Alluvium buildup reduces the capacity of the tunnel and could also damage flumes when it is rolled along with high flows. If the system is to be mothballed at this time, the tunnels should be closed off from the intakes to prevent further alluvial accumulation.

The tunnel capacities, based upon graduated depth of flows and 5 ft. wide tunnels, were computed. (See Table c)

Flumes

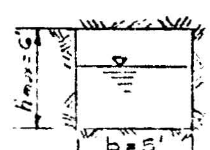
The other component of the transmission system, flumes, in many ways provides the most critical constraint on total flow. Prior to the mid 1960's the standard diameter of the flumes was 84 inches, capable of transporting up to 50 MGD, more flow than even the tunnel. Replacements were made with standard 60 inch diameter half round flumes whose

AKINAKA & ASSOCIATES, LTD.
CONSULTING ENGINEERS

PROJECT PHASE III, NORTH KOHALA WATER RESOURCES MANAGEMENT AND DEVELOPMENT STUDY DATE MAY 7, 1975 BY RYA

SUBJECT CAPACITY OF ROCK-CUT TUNNEL AND DITCH, KOHALA DITCH (AWINI SECTION) CHECKED BY ____ SHEET ____ OF ____ SHTS

| FLUME NO. | LOCATION | LENGTH (ft) | SECTION | SIZE | MATERIAL | Q (MGD) | Q (CFS) | n | S (%) | Z (H:V) | b (ft) | Vn (fps) | dn (ft) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| TYPICAL TUNNEL & DITCH | | — | RECT | 5X6 | ROCK-CUT | 1.210 | 1.8724 | .035 | .1000 | .00 | 5.00 | .74 | .50 |
| | " | — | RECT | " | " | 3.467 | 5.3641 | .035 | .1000 | .00 | 5.00 | 1.07 | 1.00 |
| | " | — | RECT | " | " | 6.234 | 9.6455 | .035 | .1000 | .00 | 5.00 | 1.28 | 1.50 |
| | " | — | RECT | " | " | 9.310 | 14.4030 | .035 | .1000 | .00 | 5.00 | 1.44 | 2.00 |
| | " | — | RECT | " | " | 12.588 | 19.4745 | .035 | .1000 | .00 | 5.00 | 1.55 | 2.50 |
| | " | — | RECT | " | " | 16.008 | 24.7651 | .035 | .1000 | .00 | 5.00 | 1.65 | 3.00 |
| | " | — | RECT | " | " | 19.531 | 30.2152 | .035 | .1000 | .00 | 5.00 | 1.72 | 3.50 |
| | " | — | RECT | " | " | 23.132 | 35.7853 | .035 | .1000 | .00 | 5.00 | 1.78 | 4.00 |
| | " | — | RECT | " | " | 26.792 | 41.4479 | .035 | .1000 | .00 | 5.00 | 1.84 | 4.50 |
| | " | — | RECT | " | " | 30.499 | 47.1834 | .035 | .1000 | .00 | 5.00 | 1.88 | 5.00 |
| | " | — | RECT | " | " | 34.245 | 52.9775 | .035 | .1000 | .00 | 5.00 | 1.92 | 5.50 |
| | " | — | RECT | " | " | 38.021 | 58.8193 | .035 | .1000 | .00 | 5.00 | 1.96 | 6.00 |




TYPICAL TUNNEL SECTION
EST. $n = 0.035$ (See V.T. CHOW, OPEN CHANNEL HYDRAULICS, 1959, p. 120)

TABLE C

capacity is no more than 35 MGD, about the same as the tunnel. A critically limiting replacement was made in Oniu gulch where two 18 inch pipes took the place of an open flume.(See Table d) The combined flow of the pipes under the transmission gradient of 0.1% is 5 - 6 MGD, and thus most of the flow from Waikaloa, Waiapuka, Kamoloumi, Makookoo, and Ohiahuea, the largest stream in the entire Awini Sector, is lost to the system. Certainly if the Sector is to be maintained, this constraint must be eliminated.

The April 1973 Kohala Corp. Inventory in the appendix of the Phase I Report by Stephen Bowles was updated by the February 1975 field trip. (See Table e)

## Adits

During the field investigation, several adits were identified. Some of the adits were only three feet above the tunnel floor, thus allowing the flows to spill. In improving the transmission capacity of the tunnels, further field investigation must be conducted to identify all adits with this characteristic. Also, if the mule trail is to be open to the public, the adits should have grill work installed at their entrances to prevent hikers from entering the adits.

## Mule Trails

In general, the mule trails are in good condition and have been maintained by the Kohala Ditch Company, being the only access to the ditch system. There was evidence of minor earthslides and trees falling on the trails during field trips. The mule bridges that cross the deep

AKINAKA & ASSOCIATES, LTD.
CONSULTING ENGINEERS

PROJECT PHASE III, NORTH KOHALA WATER RESOURCES MANAGEMENT AND DEVELOPMENT STUDY DATE MAY 7, 1975 BY RYA

SUBJECT PIPE HALF SECTION FLUME CAPACITIES - AWINI SECTION CHECKED BY SHEET OF SHTS
(n = 0.010 - smooth metal pipe)

| FLUME NO. | LOCATION | LENGTH (ft) | DIAMETER (in) | MATERIAL | Q (MGD) | Q (CFS) | n | S (%) | Aw (sq ft) | Vn (fps) | dn (ft) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | WAIAPUKA | 39(e) | 42(e) | ARMCO | 13.367 | 20.6801 | .010 | .1000 | 4.81 | 4.29 | 1.75 |
| 2 | KAHOLOUMI | 48(e) | 42(m) | " | 13.367 | 20.6801 | .010 | .1000 | 4.81 | 4.29 | 1.75 |
| 3 | NAKOOKO (EAST MAIN BR) | 58(e) | 60(m) | " | 34.604 | 53.5334 | .010 | .1000 | 9.81 | 5.45 | 2.50 |
| 4 | NAKOOKO (WEST BR) | 25.5(e) | 60(e) | " | 34.604 | 53.5334 | .010 | .1000 | 9.81 | 5.45 | 2.50 |
| 5 | OHIAHUEA | 30(e) | 60(e) | " | 34.604 | 53.5334 | .010 | .1000 | 9.81 | 5.45 | 2.50 |
| 6 | ONIU (2 - 18" pipes) | 29(e) | 18(m) | " | 5.58 ~~2.791~~ | 8.64 ~~4.3182~~ | .010 | .1000 | 1.76 | 2.44 | 1.50 |
| 7 | HONOPUE (1ST EAST BR) | 47.5(e) | 60(m) | " | 34.604 | 53.5334 | .010 | .1000 | 9.81 | 5.45 | 2.50 |
| 8 | HONOPUE (MAIN BR) | 36(e) | 60(e) | " | 34.604 | 53.5334 | .010 | .1000 | 9.81 | 5.45 | 2.50 |
| 10 | HONOKANE IKI (EAST) | 39(e) | 60(e) | " | 34.604 | 53.5334 | .010 | .1000 | 9.81 | 5.45 | 2.50 |

PROJECT PHASE III, NORTH KOHALA WATER RESOURCES MANAGEMENT AND DEVELOPMENT STUDY DATE MAY 7, 1975 BY RYA

SUBJECT RECTANGULAR SECTION FLUME CAPACITIES - AWINI SECTION CHECKED BY SHEET OF SHTS

| FLUME NO. | LOCATION | LENGTH (ft) | SECTION | SIZE | MATERIAL | Q (MGD) | Q (CFS) | n | S (%) | Z (H:V) | b (ft) | Vn (fps) | dn (ft) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 9 | HONKEA (MAIN BR) | 54(e) | RECT | 4'X5'(e) | WOOD | 55.042 | 85.1508 | .014 | .1000 | .00 | 4.00 | 4.25 | 5.00 |

NOTE: 1. (e) - ESTIMATED
(m) - MEASURED IN FIELD 2/24-26/75

TABLE d.

KOHALA DITCH - AWINI SECTOR
APRIL, 1973 KOHALA CORP. INVENTORY - FEBRUARY, 1975 FIELD TRIP

| Flume No. | Location | Length (Feet) 1973 Inv. | Size 1973 Inv. | Size 1975 Field | Material 1973 Inv. | Last Replaced 1973 Inv. | Condition 1973 Inv. | Comments Based On 1975 Field Trip |
|---|---|---|---|---|---|---|---|---|
| 1 | Waiapuka | 42 | 72 In. | Not Meas. | ARMCO | 62/63 | Good | On old Kohala Corp. Map, two flumes were shown, but only one identified in field. |
| 2 | Kamoloumi | 35 | 72 In. | 48" DIA (M) | ARMCO | 65/66 | Excellent | |
| 3 | Nakooko (East Main Branch) | 56 | 72 In. | 60" DIA (M) | ARMCO | 65/66 | Excellent | Depth of alluvial bed load is 1' (meas.). |
| 4 | Nakooko (West Branch) | 24 | 72 In. | Not Meas. | ARMCO | 65/66 | Excellent | Did not go to flume. Trail very steep and long. |
| 5 | Ohiahuea | 30 | 72 In. | Not Meas. | ARMCO | 66/67 | Excellent | Trail to intake and flume too dangerous. Did not attempt visit. |
| 6 | Oniu | 58 | 84 In. | 2 - 18" DIA Pipes (Meas.) | ARMCO | 1969 | Excellent | 2 - 18" DIA. full circle pipes. No. alluvium in pipes. |
| 7 | Honopue (1st East Branch) | 48 | 84 In. | 48" DIA (M) | ARMCO | 64/65 | Excellent | |
| 8 | Honopue (Main Branch) | 36 | 84 In. | Not Meas. | ARMCO | 62/63 | Good | Trail to intake and flume too dangerous. Did not attempt visit. |
| 9 | Honokea (Main Branch) | 54 | 4' x 5' (Est.) | Not Meas. | Wood | 64/65 | Good | Verified that flume is wooden and in good condition. |

TABLE e

valleys, i.e. Ohiahuea and Honopue, are quite old and should be inspected regularly (see photo). Any major improvements to the Awini Section of the ditch system should include construction of new mule and foot bridges to assure the continued safety of the trail system.

Foot Trails

The foot trails covered in this section refers to the access routes from the mule trail to the intakes, tunnels, and flumes. In general, these trails were over-grown with vegetation during the February, 1975 field trip and do require a higher maintenance level than do the mule trails. Some of these trails are quite dangerous for the inexperienced as well as the experienced hiker, e.g. Ohiahuea trail to intake and flume Honopue (Main Branch) trail to intake and flume Nakookoo (West Branch) trail to flume. The Kohala Ditch Company has attracted by necessity only sure-footed personnel over the years. The more dangerous trails will have to be made safer for continued operation. A steel, or cable hand rail cable system anchored to the near vertical walls should be installed. The foot trails along the canyon walls should also be made wider where possible.

Ditchmen's Houses

The Kohala Ditch Company has three sites for lodging of their ditchmen when working on the Awini and Honokane Nui Section of the ditch. (2 Honokane Nui cabins, Awini Cabin, and Kaukini Cabin on the Honopue Valley ridgeline).

All four cabins are in very good condition and have been well maintained by the Ditch Company.

The houses should be continued at their high maintenance level if the Awini ditch operations are to be continued. In addition, these cabins should be secured from vandalism.

Required Maintenance of the Existing Structures

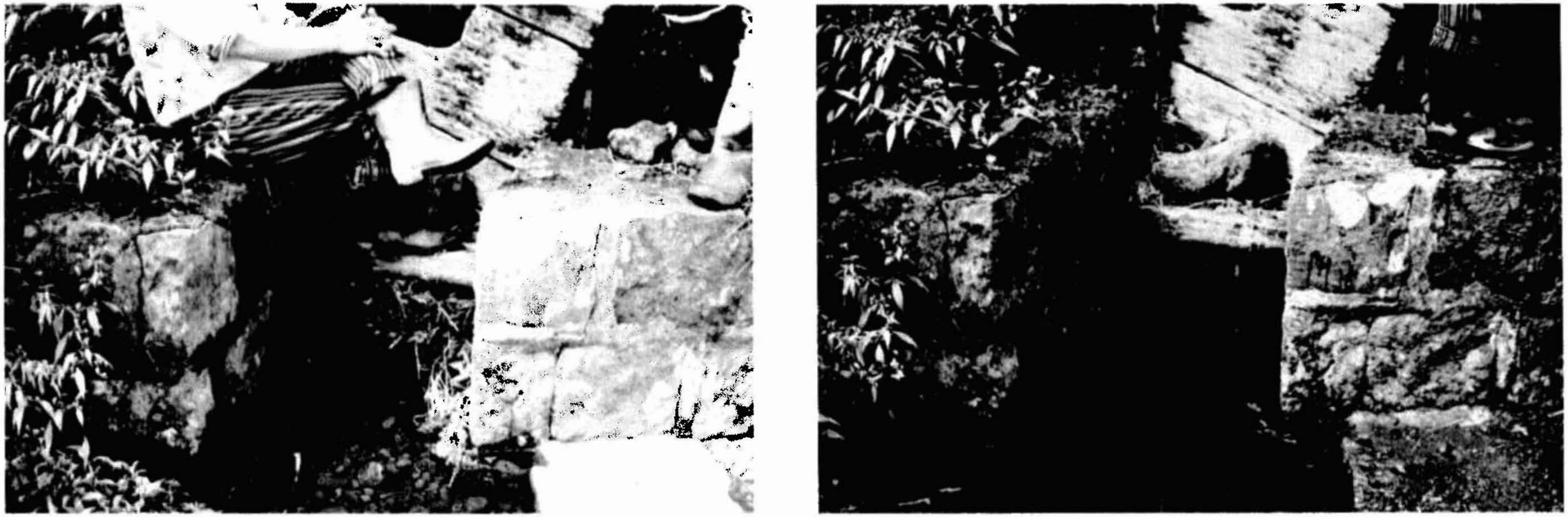
One of the important observations of the field trip is the required high maintenance of the intake structures and the need to keep the dam intakes clear of alluvium bedload and to sluice the intakes, tunnels and flumes to more fully utilize the existing ditch capacity.

To maintain the "back country" ditch system, i.e. Honokane Nui and Awini sections, a minimum of four experienced ditchmen is recommended. In support of the ditchmen and to provide some safety, it is recommended that a radio grid system be established in the "back country." In general, the radio communication system set up for the Phase III exploratory drilling was successful and provided for efficient drilling operations and safety of personnel. The field trip emphasized the value of the mules as a means of transportation for men and supplies. As long as the Awini, Honokane Nui, and Pololu systems are being operated and maintained, the necessary number of mules should be included in the ditch operation.

BEGIN KOHALA DITCH
WAIAKALOA EAST BRANCH INTAKE

KOLEALIILII INTAKE
STREAM INTAKE INTO TUNNEL DAM STRUCTURE

CLOGGED WAIAPUKA INTAKE
AND ADJACENT MULE TRAIL



BEFORE AND AFTER CLEANING
MAIN (WEST) HONOKEA INTAKE

CLEANING 2ND RIGHT BRANCH (EAST)
HONOKEA INTAKE BY KOHALA DITCH DITCHMAN

1ST RIGHT BRANCH (EAST)
HONOKEA INTAKE AFTER
CLEANING OF INTAKE

TYPICAL STEEL FLUME WITH REDWOOD FRAMING
AWINI SECTION
KAMOLOUMI FLUME (KC FLUME NO. 2)

FLOW CONSTRAINT IN AWINI SYSTEM
ONIU FLUME (KC FLUME NO. 6)
2 - 18" DIAMETER STEEL PIPE FLUME

UNCLOGGED KAILIKAULA INTAKE
MOST EFFICIENT INTAKE DUE TO
NATURAL UPSTREAM SEDIMENT TRAP BASIN

TYPICAL ADIT
(ACCESS TO TUNNEL)

OLD HONOPUE MULE BRIDGE

NARROW FOOT TRAIL TO OHIAHUEA FLUME
(KC FLUME NO. 5)

FOOT TRAIL TO KOLEALIILII INTAKE

KAUKINI CABIN OVERLOOKING HONOPUE VALLEY
FEBRUARY 1975

AWINI CABIN
FEBRUARY 1975

HONOKANE CABINS
JULY 1974

## STOCHASTIC OUTPUT OF SURFACE WATER TO THE AGRICULTURAL REGION FROM THE KOHALA DITCH SYSTEM AS MEASURED AT U.S.G.S. GAGE 7510 IN POLOLU

The statistical characteristics of flow passing U.S.G.S. Gage 7510 in Pololu Valley have already been documented to some extent in the Phase II report. In that report monthly flow duration curves are given as well as low flow frequency curves. The flow duration curves show that monthly flows are essentially normally distributed.

The flow at Gage 7510 may be treated as the input to the Kohala agricultural region from the portion of the Ditch system composed of the major sectors of Awini and East Honokane Nui, and the lesser sectors of East and West Honokane Iki, West Honokane Nui, and Pololu. The period of record analyzed extends from 1928 through 1960 (33 years), a time during which it is reasonable to assume that the Ditch System was maintained at a high level of efficiency because the plantation was relatively stable. In recent years the system has been allowed to deteriorate from benign neglect as the plantation diminished its operations.

Three approaches are used to exhibit the stochastic nature of flow past Gage 7510. The first is the historical record of flows by months and its reduction to monthly deficits or surpluses as computed from a demand model. The second is a percentile deficit-surplus model which shows the probability of either a deficit or surplus for each month when related to the demand model. The third is a simulation model which generates new serially connected flows from the statistics of the historical record. The first model, called the historical model, illustrates the variability of flows when there is no storage capacity available to augment them; from this model the storage capacity required to satisfy the demand model can be derived. The second model, called the percentile model, gives the probability of flows by month in 5% frequency intervals and the deficits or surpluses associated with the demand model. The flow data is actually a digital expression of information already included in the flow duration curves. The third model, called the synthetic hydrology model, extends the historical record by simulating 100 years of monthly flows so that drought characteristics may be evaluated. This model indicates that the 33 year historical record already includes the worst expectable 100 year flow characteristics.

In addition to these models, estimates of needed hypothetical storage capacity based on evaluation of the cumulative departures from the mean demand are made for fixed monthly demands. No matter how it is determined, whether by the simulation model or the historical model, the required storage capacity to guarantee agricultural demand is substantial. The demand deficits can be satisfied with pumped groundwater, from reservoirs, or possibly from high level dike water. The first two methods are costly, and the third, though relatively inexpensive to initiate and operate, is not likely to provide all of the water needed to meet the deficits. Therefore either groundwater or surface storage, or both, must be considered in a large scale agriculture plan.

In the Phase II report the economics of water supply were evaluated for the irrigation of 6000 acres using an average water demand of 19.5 mgd and a maximum demand of 33.6 mgd. In this report, for the sake of exemplifying the relationship between varying supply and varying demand, the demand model of Alexander is used. In this model 5327 acres of sugar cane would be irrigated with the following monthly volumes of water (values in mg):

| January | February | March | April | May | June |
|---|---|---|---|---|---|
| 628 | 626 | 744 | 788 | 910 | 946 |

| July | August | September | October | November | December |
|---|---|---|---|---|---|
| 969 | 1001 | 905 | 796 | 694 | 617 |

| Annual Total |
|---|
| 9624 |

The gross average daily demand for the above is 26.4 mgd, which is nearly equivalent to the gross average daily output at Gage 7510 of 27 mgd, and falls midway between the demand average and maximum given in Phase II. In contrast, the Kohala Plantation was accustomed to irrigating about 5500 acres with an average of 40 mgd. However, the Alexander model assumes the utilization of the most efficient technology, such as drip irrigation, whereas the Kohala Plantation used furrow and overhead irrigation.

Any demand model could be used in the computer runs, but it is not likely that practicable agricultural schemes could significantly exceed the requirements of the Alexander demand model unless large scale development of ground-water were planned. The Alexander model is a reasonable compromise to use with the flow models.

Historical Model (Deficit - Surplus)

Table I is a printout of the month by month output of Gage 7510 for the period January 1928 through December 1960. Five months of flow were not recorded (July and August, 1928; and July, August and September, 1939), for which corrections are made in the evaluations.

Table 2 lists the deficits by months, using the Alexander demand model. Where no values are shown, surpluses, as given in Table 3, occur. Values used for the missing months of record are the median values of record for those months. The tabulations show that the median expectable deficit is 744 mg/yr while the median expectable surplus is 892 mg/yr. It is clear that without surface storage much of the ditch flow would be lost for direct use in agriculture, though if allowed to percolate it would help recharge the basal lens.

The total deficit over 33 years, given the requirements of the Alexander model, would be 26,885 mg. In the Phase II Report it was noted that the direct cost of pumping ground-water to the upper ditch was about $100/mg., which if applied to the above deficit would amount to an annual cost of $81,469.00. On the other hand, surface water surplus over the 33 years would total 35,690 mg. worth \$103,151/yr. if also costed at \$100/mg. Obviously, considerable real savings could be enjoyed were there some way to store the surplus waters at the ditch elevation.

Currently the only storage capacity on the ditch system are small reservoirs capable of holding a total of about 100 mg. The pertinent question then becomes, how much capacity is needed to satisfy the demand model? The following procedure, using the historical record, yields a good estimate of the minimum capacity needed to meet all demands and of capacities capable of meeting demand for various percentages of total time. A storage capacity is assigned to the system at the start of the record and is assumed to be full, then for each month in serial order the reservoir balance is computed to determine whether or not the reservoir goes dry. If it does dry, capacity is insufficient to meet demand, but if it does dry only for limited intervals, the savings on the lower capitalization costs for a smaller than absolutely necessary reservoir might be worth the risks associated with sporadic dry-outs. For model simplicity, reservoir evaporation is assumed equal to rainfall, and leakage is ignored.

TABLE 1
KOHALA DITCH - POLOLU GAGE 7510
HISTORICAL RECORD
(FLOW IN MG/MONTH)
1928 - 1960

| YEAR | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1928 | 717 | 707 | 572 | 752 | 858 | 690 | | | 597 | 584 | 572 | 672 |
| 1929 | 839 | 717 | 721 | 936 | 809 | 679 | 980 | 950 | 846 | 553 | 785 | 839 |
| 1930 | 754 | 622 | 814 | 910 | 884 | 1000 | 566 | 527 | 317 | 280 | 580 | 826 |
| 1931 | 665 | 622 | 646 | 870 | 772 | 754 | 865 | 911 | 871 | 758 | 729 | 771 |
| 1932 | 907 | 1040 | 908 | 1080 | 922 | 1040 | 747 | 828 | 886 | 852 | 898 | 957 |
| 1933 | 1000 | 810 | 919 | 876 | 1040 | 622 | 959 | 776 | 600 | 355 | 516 | 794 |
| 1934 | 684 | 568 | 528 | 1080 | 900 | 840 | 1010 | 831 | 742 | 383 | 512 | 534 |
| 1935 | 836 | 796 | 769 | 927 | 940 | 726 | 636 | 588 | 576 | 554 | 690 | 510 |
| 1936 | 532 | 604 | 888 | 803 | 918 | 1080 | 863 | 660 | 613 | 463 | 528 | 684 |
| 1937 | 642 | 790 | 865 | 864 | 1050 | 880 | 1160 | 1280 | 944 | 809 | 758 | 883 |
| 1938 | 734 | 661 | 883 | 846 | 952 | 826 | 1170 | 958 | 806 | 751 | 716 | 739 |
| 1939 | 1100 | 751 | 964 | 812 | 838 | 1010 | | | | 678 | 561 | 819 |
| 1940 | 463 | 616 | 623 | 543 | 660 | 619 | 1220 | 1120 | 694 | 652 | 966 | 826 |
| 1941 | 641 | 560 | 899 | 760 | 988 | 936 | 806 | 957 | 642 | 591 | 684 | 518 |
| 1942 | 636 | 500 | 552 | 769 | 730 | 817 | 856 | 954 | 806 | 827 | 758 | 826 |
| 1943 | 802 | 648 | 924 | 878 | 789 | 860 | 734 | 908 | 870 | 673 | 490 | 611 |
| 1944 | 547 | 500 | 525 | 1180 | 891 | 926 | 958 | 870 | 701 | 459 | 542 | 721 |
| 1945 | 614 | 544 | 1190 | 860 | 702 | 806 | 1110 | 993 | 664 | 823 | 968 | 972 |
| 1946 | 711 | 445 | 1190 | 1140 | 773 | 703 | 674 | 858 | 689 | 650 | 816 | 807 |
| 1947 | 695 | 550 | 960 | 828 | 985 | 831 | 1140 | 920 | 704 | 631 | 710 | 694 |
| 1948 | 894 | 790 | 908 | 870 | 952 | 790 | 962 | 852 | 768 | 849 | 678 | 908 |
| 1949 | 758 | 529 | 923 | 1020 | 861 | 745 | 964 | 749 | 711 | 932 | 927 | 1040 |
| 1950 | 746 | 713 | 926 | 938 | 966 | 768 | 1120 | 977 | 709 | 855 | 1070 | 838 |
| 1951 | 874 | 872 | 714 | 794 | 723 | 788 | 1170 | 974 | 671 | 656 | 701 | 803 |
| 1952 | 1100 | 1010 | 1120 | 1130 | 1200 | 1290 | 902 | 1010 | 728 | 671 | 1010 | 875 |
| 1953 | 554 | 638 | 866 | 844 | 1090 | 857 | 1250 | 1230 | 847 | 837 | 1080 | 1110 |
| 1954 | 714 | 412 | 978 | 737 | 1060 | 1260 | 1210 | 1080 | 572 | 636 | 1020 | 1050 |
| 1955 | 548 | 242 | 468 | 923 | 1150 | 1120 | 1260 | 1470 | 840 | 713 | 528 | 376 |
| 1956 | 590 | 811 | 798 | 814 | 1120 | 1110 | 1080 | 956 | 738 | 808 | 745 | 575 |
| 1957 | 748 | 733 | 716 | 973 | 871 | 647 | 915 | 1060 | 735 | 737 | 778 | 814 |
| 1958 | 914 | 642 | 913 | 880 | 1110 | 1070 | 1110 | 1260 | 790 | 804 | 1030 | 1340 |
| 1959 | 784 | 1040 | 1040 | 1070 | 1220 | 804 | 1190 | 1270 | 746 | 818 | 750 | 1040 |
| 1960 | 868 | 842 | 926 | 1230 | 969 | 901 | 921 | 960 | 911 | 678 | 910 | 1190 |

TABLE 2
HISTORICAL MODEL (DEFICIT)
KOHALA DITCH - POLOLU GAGE 7510
(DEFICIT IN MG/MONTH)
1928 - 1960

| YEAR | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | ANNUAL TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| DEMAND | 628 | 626 | 744 | 788 | 910 | 946 | 969 | 1001 | 905 | 796 | 694 | 617 | |
| 1928 | | | 172 | 36 | 52 | 256 | 5 | 64 | 308 | 212 | 122 | | 1227 |
| 1929 | | | 23 | | 101 | 267 | | 51 | 59 | 243 | | | 744 |
| 1930 | | 4 | | | 26 | | 403 | 474 | 588 | 516 | 114 | | 2125 |
| 1931 | | 4 | 98 | | 138 | 192 | 104 | 90 | 34 | 38 | | | 698 |
| 1932 | | | | | | | 222 | 173 | 19 | | | | 414 |
| 1933 | | | | | | 324 | 10 | 225 | 305 | 441 | 178 | | 1483 |
| 1934 | | 58 | 216 | | 10 | 106 | | 170 | 163 | 413 | 182 | 83 | 1401 |
| 1935 | | | | | | 220 | 333 | 413 | 329 | 242 | 4 | 107 | 1648 |
| 1936 | 96 | 22 | | | | | 106 | 341 | 292 | 333 | 166 | | 1356 |
| 1937 | | | | | | 66 | | | | | | | 66 |
| 1938 | | | | | | 120 | | 43 | 99 | 45 | | | 307 |
| 1939 | | | | | 72 | | 5 | 64 | 174 | 118 | 133 | | 566 |
| 1940 | 165 | 10 | 121 | 245 | 250 | 327 | | | 211 | 144 | | | 1473 |
| 1941 | | 66 | | 28 | | 10 | 163 | 44 | 263 | 205 | 10 | 99 | 888 |
| 1942 | | 126 | 192 | 19 | 180 | 129 | 113 | 47 | 99 | | | | 905 |
| 1943 | | | | | 121 | 86 | 235 | 93 | 35 | 123 | 204 | 6 | 903 |
| 1944 | 81 | 126 | 219 | | 19 | 20 | 11 | 131 | 204 | 337 | 152 | | 1300 |
| 1945 | 14 | 82 | | | 208 | 140 | | 8 | 241 | | | | 693 |
| 1946 | | 181 | | | 137 | 243 | 295 | 143 | 216 | 146 | | | 1361 |
| 1947 | | 76 | | | | 115 | | 81 | 201 | 165 | | | 638 |
| 1948 | | | | | | 156 | 7 | 149 | 137 | | 16 | | 465 |
| 1949 | | 97 | | | 49 | 201 | 5 | 252 | 194 | | | | 798 |
| 1950 | | | | | | 178 | | 24 | 196 | | | | 398 |
| 1951 | | | 30 | | 187 | 158 | | 27 | 234 | 140 | | | 776 |
| 1952 | | | | | | | 67 | | 177 | 125 | | | 369 |
| 1953 | 74 | | | | | 89 | | | 58 | | | | 221 |
| 1954 | | 214 | | 51 | | | | | 333 | 160 | | | 758 |
| 1955 | 80 | 334 | 276 | | | | | | 65 | 83 | 166 | 241 | 1295 |
| 1956 | 38 | | | | | | | 45 | 167 | | | 42 | 292 |
| 1957 | | | 28 | | 39 | 299 | 54 | | 170 | 59 | | | 649 |
| 1958 | | | | | | | | | 115 | | | | 115 |
| 1959 | | | | | | 142 | | | 159 | | | | 301 |
| 1960 | | | | | | 45 | 48 | 41 | | 118 | | | 252 |
| | | | | | | | | | | | | TOTAL | 26885 |

TABLE 3
HISTORICAL MODEL (SURPLUS)
KOHALA DITCH - POLOLU GAGE 7510
(SURPLUS IN MG/MONTH)
1928 - 1960

| YEAR | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | ANNUAL TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| DEMAND | 628 | 626 | 744 | 788 | 910 | 946 | 969 | 1001 | 905 | 796 | 694 | 617 | |
| 1928 | 89 | 81 | | | | | | | | | | 55 | 225 |
| 1929 | 211 | 91 | | 148 | | | 11 | | | | 91 | 222 | 774 |
| 1930 | 126 | | 70 | 122 | | 54 | | | | | | 209 | 581 |
| 1931 | 37 | | | 82 | | | | | | | 35 | 154 | 308 |
| 1932 | 279 | 414 | 164 | 292 | 12 | 94 | | | | 56 | 204 | 340 | 1855 |
| 1933 | 372 | 184 | 175 | 88 | 130 | | | | | | | 177 | 1126 |
| 1934 | 56 | | | 292 | | | 41 | | | | | | 389 |
| 1935 | 208 | 170 | 25 | 139 | 30 | | | | | | | | 572 |
| 1936 | | | 144 | 15 | 8 | 134 | | | | | | 67 | 368 |
| 1937 | 14 | 164 | 121 | 76 | 140 | | 191 | 279 | 39 | 13 | 64 | 266 | 1367 |
| 1938 | 106 | 35 | 139 | 58 | 42 | | 201 | | | | 22 | 122 | 725 |
| 1939 | 472 | 125 | 220 | 24 | | 64 | | | | | | 202 | 1107 |
| 1940 | | | | | | | 251 | 119 | | | 272 | 209 | 851 |
| 1941 | 13 | | 155 | | 78 | | | | | | | | 246 |
| 1942 | 8 | | | | | | | | | 31 | 64 | 209 | 312 |
| 1943 | 174 | 22 | 180 | 90 | | | | | | | | | 466 |
| 1944 | | | | 392 | | | | | | | | 104 | 496 |
| 1945 | | | 446 | 72 | | | 141 | | | 27 | 274 | 355 | 1315 |
| 1946 | 83 | | 446 | 352 | | | | | | | 122 | 190 | 1193 |
| 1947 | 67 | | 216 | 40 | 75 | | 171 | | | | 16 | 77 | 662 |
| 1948 | 266 | 164 | 164 | 82 | 42 | | | | | 53 | | 291 | 1062 |
| 1949 | 130 | | 179 | 232 | | | | | | 136 | 233 | 423 | 1333 |
| 1950 | 118 | 87 | 182 | 150 | 56 | | 151 | | | 59 | 376 | 221 | 1400 |
| 1951 | 246 | 246 | | 6 | | | 201 | | | | 7 | 186 | 892 |
| 1952 | 472 | 384 | 376 | 342 | 290 | 344 | | 9 | | | 316 | 258 | 2791 |
| 1953 | | 12 | 122 | 56 | 180 | | 281 | 229 | | 41 | 386 | 493 | 1800 |
| 1954 | 86 | | 234 | | 150 | 314 | 241 | 79 | | | 326 | 433 | 1863 |
| 1955 | | | | 135 | 240 | 174 | 291 | 469 | | | | | 1309 |
| 1956 | | 185 | 54 | 26 | 210 | 164 | 111 | | | 12 | 51 | | 813 |
| 1957 | 120 | 107 | | 185 | | | | 59 | | | 84 | 197 | 752 |
| 1958 | 286 | 16 | 169 | 92 | 200 | 124 | 141 | 259 | | 8 | 336 | 723 | 2354 |
| 1959 | 156 | 414 | 296 | 282 | 310 | | 221 | 269 | | 22 | 56 | 423 | 2449 |
| 1960 | 240 | 216 | 182 | 442 | 59 | | | | 6 | | 216 | 573 | 1934 |
| | | | | | | | | | | | | TOTAL | 35690 |

The following symbols and equations describe the storage model.

$C_j$ = Storage capacity. Let j = 1000 mg, 2000 mg.......

$B_{i,j}$ = Balance in reservoir at end of month $i$.
$i$ = 1,2,........... 396

$A_i$ = Surplus or deficit for each month. Postive value is surplus, negative is deficit.

Initiating equation: $B_{i,j} = C_j + A_i$

Following equations: $B_{i,j} = B_{i-1,j} + A_i$

In all equations:

if $B_{i,j} \leq C_j$, then $B_{i,j} \equiv 0$

if $B_{i,j} > C_j$, then $B_{i,j} \equiv C_j$

Table 4 is a print-out of the storage computations.

The analysis shows that all demands at all times could be met if a storage capacity of 6000 - 7000 mg were put on the ditch system but this obviously is beyond the limit of either technical or economic feasibility. If a capacity of 1000 mg were built the reservoir would run dry 12.9% of the time; a capacity of 2000 mg would run dry 8.6% of the time; a capacity of 3000 mg would run dry 5.1% of the time; and capacities of 4000, 5000 and 6000 mg would dry out 3.0%, 1.5%, and 0.3% of the time respectively. The realistically optimum storage capacity evidently lies between 1000 and 4000 mg.

The higher capacities noted above are larger than the capacities of the largest reservoirs currently in use in Hawaii. The two largest reservoirs in the State are the

TABLE 4
STATUS OF HYPOTHETICAL
STORAGE CAPACITY OVER TIME
KOHALA DITCH - POLOLU GAUGE 7510
(RESERVOIR IN MG)
1928 - 1960

| YEAR | MONTH i | C = 1000 | C = 2000 | C = 3000 | C = 4000 | C = 5000 | C = 6000 | C = 7000 |
|---|---|---|---|---|---|---|---|---|
| 1928 | 1 | 1000.0 | 2000.0 | 3000.0 | 4000.0 | 5000.0 | 6000.0 | 7000.0 |
| | 2 | 1000.0 | 2000.0 | 3000.0 | 4000.0 | 5000.0 | 6000.0 | 7000.0 |
| | 3 | 828.0 | 1828.0 | 2828.0 | 3828.0 | 4828.0 | 5828.0 | 6828.0 |
| | 4 | 792.0 | 1792.0 | 2792.0 | 3792.0 | 4792.0 | 5792.0 | 6792.0 |
| | 5 | 740.0 | 1740.0 | 2740.0 | 3740.0 | 4740.0 | 5740.0 | 6740.0 |
| | 6 | 484.0 | 1484.0 | 2484.0 | 3484.0 | 4484.0 | 5484.0 | 6484.0 |
| | 7 | 479.0 | 1479.0 | 2479.0 | 3479.0 | 4479.0 | 5479.0 | 6479.0 |
| | 8 | 415.0 | 1415.0 | 2415.0 | 3415.0 | 4415.0 | 5415.0 | 6415.0 |
| | 9 | 107.0 | 1107.0 | 2107.0 | 3107.0 | 4107.0 | 5107.0 | 6107.0 |
| | 10 | .0 | 895.0 | 1895.0 | 2895.0 | 3895.0 | 4895.0 | 5895.0 |
| | 11 | .0 | 773.0 | 1773.0 | 2773.0 | 3773.0 | 4773.0 | 5773.0 |
| | 12 | 55.0 | 828.0 | 1828.0 | 2828.0 | 3828.0 | 4828.0 | 5828.0 |
| 1929 | 13 | 266.0 | 1039.0 | 2039.0 | 3039.0 | 4039.0 | 5039.0 | 6039.0 |
| | 14 | 357.0 | 1130.0 | 2130.0 | 3130.0 | 4130.0 | 5130.0 | 6130.0 |
| | 15 | 334.0 | 1107.0 | 2107.0 | 3107.0 | 4107.0 | 5107.0 | 6107.0 |
| | 16 | 482.0 | 1255.0 | 2255.0 | 3255.0 | 4255.0 | 5255.0 | 6255.0 |
| | 17 | 381.0 | 1154.0 | 2154.0 | 3154.0 | 4154.0 | 5154.0 | 6154.0 |
| | 18 | 114.0 | 887.0 | 1887.0 | 2887.0 | 3887.0 | 4887.0 | 5887.0 |
| | 19 | 125.0 | 898.0 | 1898.0 | 2898.0 | 3898.0 | 4898.0 | 5898.0 |
| | 20 | 74.0 | 847.0 | 1847.0 | 2847.0 | 3847.0 | 4847.0 | 5847.0 |
| | 21 | 15.0 | 788.0 | 1788.0 | 2788.0 | 3788.0 | 4788.0 | 5788.0 |
| | 22 | .0 | 545.0 | 1545.0 | 2545.0 | 3545.0 | 4545.0 | 5545.0 |
| | 23 | 91.0 | 636.0 | 1636.0 | 2636.0 | 3636.0 | 4636.0 | 5636.0 |
| | 24 | 313.0 | 858.0 | 1858.0 | 2858.0 | 3858.0 | 4858.0 | 5858.0 |
| 1930 | 25 | 439.0 | 984.0 | 1984.0 | 2984.0 | 3984.0 | 4984.0 | 5984.0 |
| | 26 | 435.0 | 980.0 | 1980.0 | 2980.0 | 3980.0 | 4980.0 | 5980.0 |
| | 27 | 505.0 | 1050.0 | 2050.0 | 3050.0 | 4050.0 | 5050.0 | 6050.0 |
| | 28 | 627.0 | 1172.0 | 2172.0 | 3172.0 | 4172.0 | 5172.0 | 6172.0 |
| | 29 | 601.0 | 1146.0 | 2146.0 | 3146.0 | 4146.0 | 5146.0 | 6146.0 |
| | 30 | 655.0 | 1200.0 | 2200.0 | 3200.0 | 4200.0 | 5200.0 | 6200.0 |
| | 31 | 252.0 | 797.0 | 1797.0 | 2797.0 | 3797.0 | 4797.0 | 5797.0 |
| | 32 | .0 | 323.0 | 1323.0 | 2323.0 | 3323.0 | 4323.0 | 5323.0 |
| | 33 | .0 | .0 | 735.0 | 1735.0 | 2735.0 | 3735.0 | 4735.0 |
| | 34 | .0 | .0 | 219.0 | 1219.0 | 2219.0 | 3219.0 | 4219.0 |
| | 35 | .0 | .0 | 105.0 | 1105.0 | 2105.0 | 3105.0 | 4105.0 |
| | 36 | 209.0 | 209.0 | 314.0 | 1314.0 | 2314.0 | 3314.0 | 4314.0 |
| 1931 | 37 | 246.0 | 246.0 | 351.0 | 1351.0 | 2351.0 | 3351.0 | 4351.0 |
| | 38 | 242.0 | 242.0 | 347.0 | 1347.0 | 2347.0 | 3347.0 | 4347.0 |
| | 39 | 144.0 | 144.0 | 249.0 | 1249.0 | 2249.0 | 3249.0 | 4249.0 |
| | 40 | 226.0 | 226.0 | 331.0 | 1331.0 | 2331.0 | 3331.0 | 4331.0 |
| | 41 | 88.0 | 88.0 | 193.0 | 1193.0 | 2193.0 | 3193.0 | 4193.0 |
| | 42 | .0 | .0 | 1.0 | 1001.0 | 2001.0 | 3001.0 | 4001.0 |

| YEAR | MONTH 1 | C = 1000 | C = 2000 | C = 3000 | C = 4000 | C = 5000 | C = 6000 | C = 7000 |
|---|---|---|---|---|---|---|---|---|
| | 43 | .0 | .0 | .0 | 897.0 | 1897.0 | 2897.0 | 3897.0 |
| | 44 | .0 | .0 | .0 | 807.0 | 1807.0 | 2807.0 | 3807.0 |
| | 45 | .0 | .0 | .0 | 773.0 | 1773.0 | 2773.0 | 3773.0 |
| | 46 | .0 | .0 | .0 | 735.0 | 1735.0 | 2735.0 | 3735.0 |
| | 47 | 35.0 | 35.0 | 35.0 | 770.0 | 1770.0 | 2770.0 | 3770.0 |
| | 48 | 189.0 | 189.0 | 189.0 | 924.0 | 1924.0 | 2924.0 | 3924.0 |
| 1932 | 49 | 468.0 | 468.0 | 468.0 | 1203.0 | 2203.0 | 3203.0 | 4203.0 |
| | 50 | 882.0 | 882.0 | 882.0 | 1617.0 | 2617.0 | 3617.0 | 4617.0 |
| | 51 | 1000.0 | 1046.0 | 1046.0 | 1781.0 | 2781.0 | 3781.0 | 4781.0 |
| | 52 | 1000.0 | 1338.0 | 1338.0 | 2073.0 | 3073.0 | 4073.0 | 5073.0 |
| | 53 | 1000.0 | 1350.0 | 1350.0 | 2085.0 | 3085.0 | 4085.0 | 5085.0 |
| | 54 | 1000.0 | 1444.0 | 1444.0 | 2179.0 | 3179.0 | 4179.0 | 5179.0 |
| | 55 | 778.0 | 1222.0 | 1222.0 | 1957.0 | 2957.0 | 3957.0 | 4957.0 |
| | 56 | 605.0 | 1049.0 | 1049.0 | 1784.0 | 2784.0 | 3784.0 | 4784.0 |
| | 57 | 586.0 | 1030.0 | 1030.0 | 1765.0 | 2765.0 | 3765.0 | 4765.0 |
| | 58 | 642.0 | 1086.0 | 1086.0 | 1821.0 | 2821.0 | 3821.0 | 4821.0 |
| | 59 | 346.0 | 1290.0 | 1290.0 | 2025.0 | 3025.0 | 4025.0 | 5025.0 |
| | 60 | 1000.0 | 1630.0 | 1630.0 | 2365.0 | 3365.0 | 4365.0 | 5365.0 |
| 1933 | 61 | 1000.0 | 2000.0 | 2002.0 | 2737.0 | 3737.0 | 4737.0 | 5737.0 |
| | 62 | 1000.0 | 2000.0 | 2186.0 | 2921.0 | 3921.0 | 4921.0 | 5921.0 |
| | 63 | 1000.0 | 2000.0 | 2361.0 | 3096.0 | 4096.0 | 5096.0 | 6096.0 |
| | 64 | 1000.0 | 2000.0 | 2449.0 | 3184.0 | 4184.0 | 5184.0 | 6184.0 |
| | 65 | 1000.0 | 2000.0 | 2579.0 | 3314.0 | 4314.0 | 5314.0 | 6314.0 |
| | 66 | 676.0 | 1676.0 | 2255.0 | 2990.0 | 3990.0 | 4990.0 | 5990.0 |
| | 67 | 666.0 | 1666.0 | 2245.0 | 2980.0 | 3980.0 | 4980.0 | 5980.0 |
| | 68 | 441.0 | 1441.0 | 2020.0 | 2755.0 | 3755.0 | 4755.0 | 5755.0 |
| | 69 | 136.0 | 1136.0 | 1715.0 | 2450.0 | 3450.0 | 4450.0 | 5450.0 |
| | 70 | .0 | 695.0 | 1274.0 | 2009.0 | 3009.0 | 4009.0 | 5009.0 |
| | 71 | .0 | 517.0 | 1096.0 | 1831.0 | 2831.0 | 3831.0 | 4831.0 |
| | 72 | 177.0 | 694.0 | 1273.0 | 2008.0 | 3008.0 | 4008.0 | 5008.0 |
| 1934 | 73 | 233.0 | 750.0 | 1329.0 | 2064.0 | 3064.0 | 4064.0 | 5064.0 |
| | 74 | 175.0 | 692.0 | 1271.0 | 2006.0 | 3006.0 | 4006.0 | 5006.0 |
| | 75 | .0 | 476.0 | 1055.0 | 1790.0 | 2790.0 | 3790.0 | 4790.0 |
| | 76 | 292.0 | 768.0 | 1347.0 | 2082.0 | 3082.0 | 4032.0 | 5032.0 |
| | 77 | 282.0 | 758.0 | 1337.0 | 2072.0 | 3072.0 | 4072.0 | 5072.0 |
| | 78 | 176.0 | 652.0 | 1231.0 | 1966.0 | 2966.0 | 3966.0 | 4966.0 |
| | 79 | 217.0 | 693.0 | 1272.0 | 2007.0 | 3007.0 | 4007.0 | 5007.0 |
| | 80 | 47.0 | 523.0 | 1102.0 | 1837.0 | 2837.0 | 3837.0 | 4837.0 |
| | 81 | .0 | 360.0 | 939.0 | 1674.0 | 2674.0 | 3674.0 | 4674.0 |
| | 82 | .0 | .0 | 526.0 | 1261.0 | 2261.0 | 3261.0 | 4261.0 |
| | 83 | .0 | .0 | 344.0 | 1079.0 | 2079.0 | 3079.0 | 4079.0 |
| | 84 | .0 | .0 | 261.0 | 996.0 | 1996.0 | 2996.0 | 3996.0 |
| 1935 | 85 | 208.0 | 208.0 | 469.0 | 1204.0 | 2204.0 | 3204.0 | 4204.0 |
| | 86 | 378.0 | 378.0 | 639.0 | 1374.0 | 2374.0 | 3374.0 | 4374.0 |
| | 87 | 403.0 | 403.0 | 664.0 | 1399.0 | 2399.0 | 3399.0 | 4399.0 |
| | 88 | 542.0 | 542.0 | 803.0 | 1538.0 | 2538.0 | 3538.0 | 4538.0 |
| | 89 | 572.0 | 572.0 | 833.0 | 1568.0 | 2568.0 | 3568.0 | 4568.0 |
| | 90 | 352.0 | 352.0 | 613.0 | 1348.0 | 2348.0 | 3348.0 | 4348.0 |

SHEET 2 OF 9 SHEETS

TABLE 4

| YEAR | MONTH I | C = 1000 | C = 2000 | C = 3000 | C = 4000 | C = 5000 | C = 6000 | C = 7000 |
|---|---|---|---|---|---|---|---|---|
| | 91 | 19.0 | 19.0 | 280.0 | 1015.0 | 2015.0 | 3015.0 | 4015.0 |
| | 92 | .0 | .0 | .0 | 602.0 | 1602.0 | 2602.0 | 3602.0 |
| | 93 | .0 | .0 | .0 | 273.0 | 1273.0 | 2273.0 | 3273.0 |
| | 94 | .0 | .0 | .0 | 31.0 | 1031.0 | 2031.0 | 3031.0 |
| | 95 | .0 | .0 | .0 | 27.0 | 1027.0 | 2027.0 | 3027.0 |
| | 96 | .0 | .0 | .0 | .0 | 920.0 | 1920.0 | 2920.0 |
| 1936 | 97 | .0 | .0 | .0 | .0 | 824.0 | 1824.0 | 2824.0 |
| | 98 | .0 | .0 | .0 | .0 | 802.0 | 1802.0 | 2802.0 |
| | 99 | 144.0 | 144.0 | 144.0 | 144.0 | 946.0 | 1946.0 | 2946.0 |
| | 100 | 159.0 | 159.0 | 159.0 | 159.0 | 961.0 | 1961.0 | 2961.0 |
| | 101 | 167.0 | 167.0 | 167.0 | 167.0 | 969.0 | 1969.0 | 2969.0 |
| | 102 | 301.0 | 301.0 | 301.0 | 301.0 | 1103.0 | 2103.0 | 3103.0 |
| | 103 | 195.0 | 195.0 | 195.0 | 195.0 | 997.0 | 1997.0 | 2997.0 |
| | 104 | .0 | .0 | .0 | .0 | 656.0 | 1656.0 | 2656.0 |
| | 105 | .0 | .0 | .0 | .0 | 364.0 | 1364.0 | 2364.0 |
| | 106 | .0 | .0 | .0 | .0 | 31.0 | 1031.0 | 2031.0 |
| | 107 | .0 | .0 | .0 | .0 | .0 | 865.0 | 1865.0 |
| | 108 | 67.0 | 67.0 | 67.0 | 67.0 | 67.0 | 932.0 | 1932.0 |
| 1937 | 109 | 81.0 | 81.0 | 81.0 | 81.0 | 81.0 | 946.0 | 1946.0 |
| | 110 | 245.0 | 245.0 | 245.0 | 245.0 | 245.0 | 1110.0 | 2110.0 |
| | 111 | 366.0 | 366.0 | 366.0 | 366.0 | 366.0 | 1231.0 | 2231.0 |
| | 112 | 442.0 | 442.0 | 442.0 | 442.0 | 442.0 | 1307.0 | 2307.0 |
| | 113 | 582.0 | 582.0 | 582.0 | 582.0 | 582.0 | 1447.0 | 2447.0 |
| | 114 | 516.0 | 516.0 | 516.0 | 516.0 | 516.0 | 1381.0 | 2381.0 |
| | 115 | 707.0 | 707.0 | 707.0 | 707.0 | 707.0 | 1572.0 | 2572.0 |
| | 116 | 986.0 | 986.0 | 986.0 | 986.0 | 986.0 | 1851.0 | 2851.0 |
| | 117 | 1000.0 | 1025.0 | 1025.0 | 1025.0 | 1025.0 | 1890.0 | 2890.0 |
| | 118 | 1000.0 | 1038.0 | 1038.0 | 1038.0 | 1038.0 | 1903.0 | 2903.0 |
| | 119 | 1000.0 | 1102.0 | 1102.0 | 1102.0 | 1102.0 | 1967.0 | 2967.0 |
| | 120 | 1000.0 | 1368.0 | 1368.0 | 1368.0 | 1368.0 | 2233.0 | 3233.0 |
| 1938 | 121 | 1000.0 | 1474.0 | 1474.0 | 1474.0 | 1474.0 | 2339.0 | 3339.0 |
| | 122 | 1000.0 | 1509.0 | 1509.0 | 1509.0 | 1509.0 | 2374.0 | 3374.0 |
| | 123 | 1000.0 | 1648.0 | 1648.0 | 1648.0 | 1648.0 | 2513.0 | 3513.0 |
| | 124 | 1000.0 | 1706.0 | 1706.0 | 1706.0 | 1706.0 | 2571.0 | 3571.0 |
| | 125 | 1000.0 | 1748.0 | 1748.0 | 1748.0 | 1748.0 | 2613.0 | 3613.0 |
| | 126 | 880.0 | 1628.0 | 1628.0 | 1628.0 | 1628.0 | 2493.0 | 3493.0 |
| | 127 | 1000.0 | 1829.0 | 1829.0 | 1829.0 | 1829.0 | 2694.0 | 3694.0 |
| | 128 | 957.0 | 1786.0 | 1786.0 | 1786.0 | 1786.0 | 2651.0 | 3651.0 |
| | 129 | 858.0 | 1687.0 | 1687.0 | 1687.0 | 1687.0 | 2552.0 | 3552.0 |
| | 130 | 813.0 | 1642.0 | 1642.0 | 1642.0 | 1642.0 | 2507.0 | 3507.0 |
| | 131 | 835.0 | 1664.0 | 1664.0 | 1664.0 | 1664.0 | 2529.0 | 3529.0 |
| | 132 | 957.0 | 1786.0 | 1786.0 | 1786.0 | 1786.0 | 2651.0 | 3651.0 |
| 1939 | 133 | 1000.0 | 2000.0 | 2258.0 | 2258.0 | 2258.0 | 3123.0 | 4123.0 |
| | 134 | 1000.0 | 2000.0 | 2383.0 | 2383.0 | 2383.0 | 3248.0 | 4248.0 |
| | 135 | 1000.0 | 2000.0 | 2603.0 | 2603.0 | 2603.0 | 3468.0 | 4468.0 |
| | 136 | 1000.0 | 2000.0 | 2627.0 | 2627.0 | 2627.0 | 3492.0 | 4492.0 |
| | 137 | 928.0 | 1928.0 | 2555.0 | 2555.0 | 2555.0 | 3420.0 | 4420.0 |
| | 138 | 992.0 | 1992.0 | 2619.0 | 2619.0 | 2619.0 | 3484.0 | 4484.0 |

TABLE 4

| YEAR | MONTH 1 | C = 1000 | C = 2000 | C = 3000 | C = 4000 | C = 5000 | C = 6000 | C = 7000 |
|---|---|---|---|---|---|---|---|---|
| | 139 | 987.0 | 1987.0 | 2614.0 | 2614.0 | 2614.0 | 3479.0 | 4479.0 |
| | 140 | 923.0 | 1923.0 | 2550.0 | 2550.0 | 2550.0 | 3415.0 | 4415.0 |
| | 141 | 749.0 | 1749.0 | 2376.0 | 2376.0 | 2376.0 | 3241.0 | 4241.0 |
| | 142 | 631.0 | 1631.0 | 2258.0 | 2258.0 | 2258.0 | 3123.0 | 4123.0 |
| | 143 | 498.0 | 1498.0 | 2125.0 | 2125.0 | 2125.0 | 2990.0 | 3990.0 |
| | 144 | 700.0 | 1700.0 | 2327.0 | 2327.0 | 2327.0 | 3192.0 | 4192.0 |
| 1940 | 145 | 535.0 | 1535.0 | 2162.0 | 2162.0 | 2162.0 | 3027.0 | 4027.0 |
| | 146 | 525.0 | 1525.0 | 2152.0 | 2152.0 | 2152.0 | 3017.0 | 4017.0 |
| | 147 | 404.0 | 1404.0 | 2031.0 | 2031.0 | 2031.0 | 2896.0 | 3896.0 |
| | 148 | 159.0 | 1159.0 | 1786.0 | 1786.0 | 1786.0 | 2651.0 | 3651.0 |
| | 149 | .0 | 909.0 | 1536.0 | 1536.0 | 1536.0 | 2401.0 | 3401.0 |
| | 150 | .0 | 582.0 | 1209.0 | 1209.0 | 1209.0 | 2074.0 | 3074.0 |
| | 151 | 251.0 | 833.0 | 1460.0 | 1460.0 | 1460.0 | 2325.0 | 3325.0 |
| | 152 | 370.0 | 952.0 | 1579.0 | 1579.0 | 1579.0 | 2444.0 | 3444.0 |
| | 153 | 159.0 | 741.0 | 1368.0 | 1368.0 | 1368.0 | 2233.0 | 3233.0 |
| | 154 | 15.0 | 597.0 | 1224.0 | 1224.0 | 1224.0 | 2089.0 | 3089.0 |
| | 155 | 287.0 | 869.0 | 1496.0 | 1496.0 | 1496.0 | 2361.0 | 3361.0 |
| | 156 | 496.0 | 1078.0 | 1705.0 | 1705.0 | 1705.0 | 2570.0 | 3570.0 |
| 1941 | 157 | 509.0 | 1091.0 | 1718.0 | 1718.0 | 1718.0 | 2583.0 | 3583.0 |
| | 158 | 443.0 | 1025.0 | 1652.0 | 1652.0 | 1652.0 | 2517.0 | 3517.0 |
| | 159 | 598.0 | 1180.0 | 1807.0 | 1807.0 | 1807.0 | 2672.0 | 3672.0 |
| | 160 | 570.0 | 1152.0 | 1779.0 | 1779.0 | 1779.0 | 2644.0 | 3644.0 |
| | 161 | 648.0 | 1230.0 | 1857.0 | 1857.0 | 1857.0 | 2722.0 | 3722.0 |
| | 162 | 638.0 | 1220.0 | 1847.0 | 1847.0 | 1847.0 | 2712.0 | 3712.0 |
| | 163 | 475.0 | 1057.0 | 1684.0 | 1684.0 | 1684.0 | 2549.0 | 3549.0 |
| | 164 | 431.0 | 1013.0 | 1640.0 | 1640.0 | 1640.0 | 2505.0 | 3505.0 |
| | 165 | 168.0 | 750.0 | 1377.0 | 1377.0 | 1377.0 | 2242.0 | 3242.0 |
| | 166 | .0 | 545.0 | 1172.0 | 1172.0 | 1172.0 | 2037.0 | 3037.0 |
| | 167 | .0 | 535.0 | 1162.0 | 1162.0 | 1162.0 | 2027.0 | 3027.0 |
| | 168 | .0 | 436.0 | 1063.0 | 1063.0 | 1063.0 | 1928.0 | 2928.0 |
| 1942 | 169 | 8.0 | 444.0 | 1071.0 | 1071.0 | 1071.0 | 1936.0 | 2936.0 |
| | 170 | .0 | 318.0 | 945.0 | 945.0 | 945.0 | 1810.0 | 2810.0 |
| | 171 | .0 | 126.0 | 753.0 | 753.0 | 753.0 | 1618.0 | 2618.0 |
| | 172 | .0 | 107.0 | 734.0 | 734.0 | 734.0 | 1599.0 | 2599.0 |
| | 173 | .0 | .0 | 554.0 | 554.0 | 554.0 | 1419.0 | 2419.0 |
| | 174 | .0 | .0 | 425.0 | 425.0 | 425.0 | 1290.0 | 2290.0 |
| | 175 | .0 | .0 | 312.0 | 312.0 | 312.0 | 1177.0 | 2177.0 |
| | 176 | .0 | .0 | 265.0 | 265.0 | 265.0 | 1130.0 | 2130.0 |
| | 177 | .0 | .0 | 166.0 | 166.0 | 166.0 | 1031.0 | 2031.0 |
| | 178 | 31.0 | 31.0 | 197.0 | 197.0 | 197.0 | 1062.0 | 2062.0 |
| | 179 | 95.0 | 95.0 | 261.0 | 261.0 | 261.0 | 1126.0 | 2126.0 |
| | 180 | 304.0 | 304.0 | 470.0 | 470.0 | 470.0 | 1335.0 | 2335.0 |
| 1943 | 181 | 478.0 | 478.0 | 644.0 | 644.0 | 644.0 | 1509.0 | 2509.0 |
| | 182 | 500.0 | 500.0 | 666.0 | 666.0 | 666.0 | 1531.0 | 2531.0 |
| | 183 | 680.0 | 680.0 | 846.0 | 846.0 | 846.0 | 1711.0 | 2711.0 |
| | 184 | 770.0 | 770.0 | 936.0 | 936.0 | 936.0 | 1801.0 | 2801.0 |
| | 185 | 649.0 | 649.0 | 815.0 | 815.0 | 815.0 | 1680.0 | 2680.0 |
| | 186 | 563.0 | 563.0 | 729.0 | 729.0 | 729.0 | 1594.0 | 2594.0 |

TABLE 4

| YEAR | MONTH 1 | C = 1000 | C = 2000 | C = 3000 | C = 4000 | C = 5000 | C = 6000 | C = 7000 |
|---|---|---|---|---|---|---|---|---|
| | 187 | 328.0 | 328.0 | 494.0 | 494.0 | 494.0 | 1359.0 | 2359.0 |
| | 188 | 235.0 | 235.0 | 401.0 | 401.0 | 401.0 | 1266.0 | 2266.0 |
| | 189 | 200.0 | 200.0 | 366.0 | 366.0 | 366.0 | 1231.0 | 2231.0 |
| | 190 | 77.0 | 77.0 | 243.0 | 243.0 | 243.0 | 1108.0 | 2108.0 |
| | 191 | .0 | .0 | 39.0 | 39.0 | 39.0 | 904.0 | 1904.0 |
| | 192 | .0 | .0 | 33.0 | 33.0 | 33.0 | 898.0 | 1898.0 |
| 1944 | 193 | .0 | .0 | .0 | .0 | .0 | 817.0 | 1817.0 |
| | 194 | .0 | .0 | .0 | .0 | .0 | 691.0 | 1691.0 |
| | 195 | .0 | .0 | .0 | .0 | .0 | 472.0 | 1472.0 |
| | 196 | 392.0 | 392.0 | 392.0 | 392.0 | 392.0 | 864.0 | 1864.0 |
| | 197 | 373.0 | 373.0 | 373.0 | 373.0 | 373.0 | 845.0 | 1845.0 |
| | 198 | 353.0 | 353.0 | 353.0 | 353.0 | 353.0 | 825.0 | 1825.0 |
| | 199 | 342.0 | 342.0 | 342.0 | 342.0 | 342.0 | 814.0 | 1814.0 |
| | 200 | 211.0 | 211.0 | 211.0 | 211.0 | 211.0 | 683.0 | 1683.0 |
| | 201 | 7.0 | 7.0 | 7.0 | 7.0 | 7.0 | 479.0 | 1479.0 |
| | 202 | .0 | .0 | .0 | .0 | .0 | 142.0 | 1142.0 |
| | 203 | .0 | .0 | .0 | .0 | .0 | .0 | 990.0 |
| | 204 | 104.0 | 104.0 | 104.0 | 104.0 | 104.0 | 104.0 | 1094.0 |
| 1945 | 205 | 90.0 | 90.0 | 90.0 | 90.0 | 90.0 | 90.0 | 1080.0 |
| | 206 | 8.0 | 8.0 | 8.0 | 8.0 | 8.0 | 8.0 | 998.0 |
| | 207 | 454.0 | 454.0 | 454.0 | 454.0 | 454.0 | 454.0 | 1444.0 |
| | 208 | 526.0 | 526.0 | 526.0 | 526.0 | 526.0 | 526.0 | 1516.0 |
| | 209 | 318.0 | 318.0 | 318.0 | 318.0 | 318.0 | 318.0 | 1308.0 |
| | 210 | 178.0 | 178.0 | 178.0 | 178.0 | 178.0 | 178.0 | 1168.0 |
| | 211 | 319.0 | 319.0 | 319.0 | 319.0 | 319.0 | 319.0 | 1309.0 |
| | 212 | 311.0 | 311.0 | 311.0 | 311.0 | 311.0 | 311.0 | 1301.0 |
| | 213 | 70.0 | 70.0 | 70.0 | 70.0 | 70.0 | 70.0 | 1060.0 |
| | 214 | 97.0 | 97.0 | 97.0 | 97.0 | 97.0 | 97.0 | 1087.0 |
| | 215 | 371.0 | 371.0 | 371.0 | 371.0 | 371.0 | 371.0 | 1361.0 |
| | 216 | 726.0 | 726.0 | 726.0 | 726.0 | 726.0 | 726.0 | 1716.0 |
| 1946 | 217 | 809.0 | 809.0 | 809.0 | 809.0 | 809.0 | 809.0 | 1799.0 |
| | 218 | 628.0 | 628.0 | 628.0 | 628.0 | 628.0 | 628.0 | 1618.0 |
| | 219 | 1000.0 | 1074.0 | 1074.0 | 1074.0 | 1074.0 | 1074.0 | 2064.0 |
| | 220 | 1000.0 | 1426.0 | 1426.0 | 1426.0 | 1426.0 | 1426.0 | 2416.0 |
| | 221 | 863.0 | 1289.0 | 1289.0 | 1289.0 | 1289.0 | 1289.0 | 2279.0 |
| | 222 | 620.0 | 1046.0 | 1046.0 | 1046.0 | 1046.0 | 1046.0 | 2036.0 |
| | 223 | 325.0 | 751.0 | 751.0 | 751.0 | 751.0 | 751.0 | 1741.0 |
| | 224 | 182.0 | 608.0 | 608.0 | 608.0 | 608.0 | 608.0 | 1598.0 |
| | 225 | .0 | 392.0 | 392.0 | 392.0 | 392.0 | 392.0 | 1382.0 |
| | 226 | .0 | 246.0 | 246.0 | 246.0 | 246.0 | 246.0 | 1236.0 |
| | 227 | 122.0 | 368.0 | 368.0 | 368.0 | 368.0 | 368.0 | 1358.0 |
| | 228 | 312.0 | 558.0 | 558.0 | 558.0 | 558.0 | 558.0 | 1548.0 |
| 1947 | 229 | 379.0 | 625.0 | 625.0 | 625.0 | 625.0 | 625.0 | 1615.0 |
| | 230 | 303.0 | 549.0 | 549.0 | 549.0 | 549.0 | 549.0 | 1539.0 |
| | 231 | 519.0 | 765.0 | 765.0 | 765.0 | 765.0 | 765.0 | 1755.0 |
| | 232 | 559.0 | 805.0 | 805.0 | 805.0 | 805.0 | 805.0 | 1795.0 |
| | 233 | 634.0 | 880.0 | 880.0 | 880.0 | 880.0 | 880.0 | 1870.0 |
| | 234 | 519.0 | 765.0 | 765.0 | 765.0 | 765.0 | 765.0 | 1755.0 |

| YEAR | MONTH 1 | C = 1000 | C = 2000 | C = 3000 | C = 4000 | C = 5000 | C = 6000 | C = 7000 |
|---|---|---|---|---|---|---|---|---|
| | 235 | 690.0 | 936.0 | 936.0 | 936.0 | 936.0 | 936.0 | 1926.0 |
| | 236 | 609.0 | 855.0 | 855.0 | 855.0 | 855.0 | 855.0 | 1845.0 |
| | 237 | 408.0 | 654.0 | 654.0 | 654.0 | 654.0 | 654.0 | 1644.0 |
| | 238 | 243.0 | 489.0 | 489.0 | 489.0 | 489.0 | 489.0 | 1479.0 |
| | 239 | 259.0 | 505.0 | 505.0 | 505.0 | 505.0 | 505.0 | 1495.0 |
| | 240 | 336.0 | 582.0 | 582.0 | 582.0 | 582.0 | 582.0 | 1572.0 |
| 1948 | 241 | 602.0 | 848.0 | 848.0 | 848.0 | 848.0 | 848.0 | 1838.0 |
| | 242 | 766.0 | 1012.0 | 1012.0 | 1012.0 | 1012.0 | 1012.0 | 2002.0 |
| | 243 | 930.0 | 1176.0 | 1176.0 | 1176.0 | 1176.0 | 1176.0 | 2166.0 |
| | 244 | 1000.0 | 1258.0 | 1258.0 | 1258.0 | 1258.0 | 1258.0 | 2248.0 |
| | 245 | 1000.0 | 1300.0 | 1300.0 | 1300.0 | 1300.0 | 1300.0 | 2290.0 |
| | 246 | 844.0 | 1144.0 | 1144.0 | 1144.0 | 1144.0 | 1144.0 | 2134.0 |
| | 247 | 837.0 | 1137.0 | 1137.0 | 1137.0 | 1137.0 | 1137.0 | 2127.0 |
| | 248 | 688.0 | 988.0 | 988.0 | 988.0 | 988.0 | 988.0 | 1978.0 |
| | 249 | 551.0 | 851.0 | 851.0 | 851.0 | 851.0 | 851.0 | 1841.0 |
| | 250 | 604.0 | 904.0 | 904.0 | 904.0 | 904.0 | 904.0 | 1894.0 |
| | 251 | 588.0 | 888.0 | 888.0 | 888.0 | 888.0 | 888.0 | 1878.0 |
| | 252 | 879.0 | 1179.0 | 1179.0 | 1179.0 | 1179.0 | 1179.0 | 2169.0 |
| 1949 | 253 | 1000.0 | 1309.0 | 1309.0 | 1309.0 | 1309.0 | 1309.0 | 2299.0 |
| | 254 | 903.0 | 1212.0 | 1212.0 | 1212.0 | 1212.0 | 1212.0 | 2202.0 |
| | 255 | 1000.0 | 1391.0 | 1391.0 | 1391.0 | 1391.0 | 1391.0 | 2381.0 |
| | 256 | 1000.0 | 1623.0 | 1623.0 | 1623.0 | 1623.0 | 1623.0 | 2613.0 |
| | 257 | 951.0 | 1574.0 | 1574.0 | 1574.0 | 1574.0 | 1574.0 | 2564.0 |
| | 258 | 750.0 | 1373.0 | 1373.0 | 1373.0 | 1373.0 | 1373.0 | 2363.0 |
| | 259 | 745.0 | 1368.0 | 1368.0 | 1368.0 | 1368.0 | 1368.0 | 2358.0 |
| | 260 | 493.0 | 1116.0 | 1116.0 | 1116.0 | 1116.0 | 1116.0 | 2106.0 |
| | 261 | 299.0 | 922.0 | 922.0 | 922.0 | 922.0 | 922.0 | 1912.0 |
| | 262 | 435.0 | 1058.0 | 1058.0 | 1058.0 | 1058.0 | 1058.0 | 2048.0 |
| | 263 | 668.0 | 1291.0 | 1291.0 | 1291.0 | 1291.0 | 1291.0 | 2281.0 |
| | 264 | 1000.0 | 1714.0 | 1714.0 | 1714.0 | 1714.0 | 1714.0 | 2704.0 |
| 1950 | 265 | 1000.0 | 1832.0 | 1832.0 | 1832.0 | 1832.0 | 1832.0 | 2822.0 |
| | 266 | 1000.0 | 1919.0 | 1919.0 | 1919.0 | 1919.0 | 1919.0 | 2909.0 |
| | 267 | 1000.0 | 2000.0 | 2101.0 | 2101.0 | 2101.0 | 2101.0 | 3091.0 |
| | 268 | 1000.0 | 2000.0 | 2251.0 | 2251.0 | 2251.0 | 2251.0 | 3241.0 |
| | 269 | 1000.0 | 2000.0 | 2307.0 | 2307.0 | 2307.0 | 2307.0 | 3297.0 |
| | 270 | 822.0 | 1822.0 | 2129.0 | 2129.0 | 2129.0 | 2129.0 | 3119.0 |
| | 271 | 973.0 | 1973.0 | 2280.0 | 2280.0 | 2280.0 | 2280.0 | 3270.0 |
| | 272 | 949.0 | 1949.0 | 2256.0 | 2256.0 | 2256.0 | 2256.0 | 3246.0 |
| | 273 | 753.0 | 1753.0 | 2060.0 | 2060.0 | 2060.0 | 2060.0 | 3050.0 |
| | 274 | 812.0 | 1812.0 | 2119.0 | 2119.0 | 2119.0 | 2119.0 | 3109.0 |
| | 275 | 1000.0 | 2000.0 | 2495.0 | 2495.0 | 2495.0 | 2495.0 | 3485.0 |
| | 276 | 1000.0 | 2000.0 | 2716.0 | 2716.0 | 2716.0 | 2716.0 | 3706.0 |
| 1951 | 277 | 1000.0 | 2000.0 | 2962.0 | 2962.0 | 2962.0 | 2962.0 | 3952.0 |
| | 278 | 1000.0 | 2000.0 | 3000.0 | 3208.0 | 3208.0 | 3208.0 | 4198.0 |
| | 279 | 970.0 | 1970.0 | 2970.0 | 3178.0 | 3178.0 | 3178.0 | 4168.0 |
| | 280 | 976.0 | 1976.0 | 2976.0 | 3184.0 | 3184.0 | 3184.0 | 4174.0 |
| | 281 | 789.0 | 1789.0 | 2789.0 | 2997.0 | 2997.0 | 2997.0 | 3987.0 |
| | 282 | 631.0 | 1631.0 | 2631.0 | 2839.0 | 2839.0 | 2839.0 | 3829.0 |

| YEAR | MONTH 1 | C = 1000 | C = 2000 | C = 3000 | C = 4000 | C = 5000 | C = 6000 | C = 7000 |
|---|---|---|---|---|---|---|---|---|
| | 283 | 832.0 | 1832.0 | 2832.0 | 3040.0 | 3040.0 | 3040.0 | 4030.0 |
| | 284 | 805.0 | 1805.0 | 2805.0 | 3013.0 | 3013.0 | 3013.0 | 4003.0 |
| | 285 | 571.0 | 1571.0 | 2571.0 | 2779.0 | 2779.0 | 2779.0 | 3769.0 |
| | 286 | 431.0 | 1431.0 | 2431.0 | 2639.0 | 2639.0 | 2639.0 | 3629.0 |
| | 287 | 438.0 | 1438.0 | 2438.0 | 2646.0 | 2646.0 | 2646.0 | 3636.0 |
| | 288 | 624.0 | 1624.0 | 2624.0 | 2832.0 | 2832.0 | 2832.0 | 3822.0 |
| 1952 | 289 | 1000.0 | 2000.0 | 3000.0 | 3304.0 | 3304.0 | 3304.0 | 4294.0 |
| | 290 | 1000.0 | 2000.0 | 3000.0 | 3688.0 | 3688.0 | 3688.0 | 4678.0 |
| | 291 | 1000.0 | 2000.0 | 3000.0 | 4000.0 | 4064.0 | 4064.0 | 5054.0 |
| | 292 | 1000.0 | 2000.0 | 3000.0 | 4000.0 | 4406.0 | 4406.0 | 5396.0 |
| | 293 | 1000.0 | 2000.0 | 3000.0 | 4000.0 | 4696.0 | 4696.0 | 5686.0 |
| | 294 | 1000.0 | 2000.0 | 3000.0 | 4000.0 | 5000.0 | 5040.0 | 6030.0 |
| | 295 | 933.0 | 1933.0 | 2933.0 | 3933.0 | 4933.0 | 4973.0 | 5963.0 |
| | 296 | 942.0 | 1942.0 | 2942.0 | 3942.0 | 4942.0 | 4932.0 | 5972.0 |
| | 297 | 765.0 | 1765.0 | 2765.0 | 3765.0 | 4765.0 | 4805.0 | 5795.0 |
| | 298 | 640.0 | 1640.0 | 2640.0 | 3640.0 | 4640.0 | 4680.0 | 5670.0 |
| | 299 | 956.0 | 1956.0 | 2956.0 | 3956.0 | 4956.0 | 4996.0 | 5936.0 |
| | 300 | 1000.0 | 2000.0 | 3000.0 | 4000.0 | 5000.0 | 5254.0 | 6244.0 |
| 1953 | 301 | 926.0 | 1926.0 | 2926.0 | 3926.0 | 4926.0 | 5130.0 | 6170.0 |
| | 302 | 938.0 | 1938.0 | 2938.0 | 3938.0 | 4938.0 | 5192.0 | 6182.0 |
| | 303 | 1000.0 | 2000.0 | 3000.0 | 4000.0 | 5000.0 | 5314.0 | 6304.0 |
| | 304 | 1000.0 | 2000.0 | 3000.0 | 4000.0 | 5000.0 | 5370.0 | 6360.0 |
| | 305 | 1000.0 | 2000.0 | 3000.0 | 4000.0 | 5000.0 | 5550.0 | 6540.0 |
| | 306 | 911.0 | 1911.0 | 2911.0 | 3911.0 | 4911.0 | 5461.0 | 6451.0 |
| | 307 | 1000.0 | 2000.0 | 3000.0 | 4000.0 | 5000.0 | 5742.0 | 6732.0 |
| | 308 | 1000.0 | 2000.0 | 3000.0 | 4000.0 | 5000.0 | 5971.0 | 6961.0 |
| | 309 | 942.0 | 1942.0 | 2942.0 | 3942.0 | 4942.0 | 5913.0 | 6903.0 |
| | 310 | 983.0 | 1983.0 | 2983.0 | 3983.0 | 4983.0 | 5954.0 | 6944.0 |
| | 311 | 1000.0 | 2000.0 | 3000.0 | 4000.0 | 5000.0 | 6000.0 | 7000.0 |
| | 312 | 1000.0 | 2000.0 | 3000.0 | 4000.0 | 5000.0 | 6000.0 | 7000.0 |
| 1954 | 313 | 1000.0 | 2000.0 | 3000.0 | 4000.0 | 5000.0 | 6000.0 | 7000.0 |
| | 314 | 786.0 | 1786.0 | 2786.0 | 3786.0 | 4786.0 | 5786.0 | 6786.0 |
| | 315 | 1000.0 | 2000.0 | 3000.0 | 4000.0 | 5000.0 | 6000.0 | 7000.0 |
| | 316 | 949.0 | 1949.0 | 2949.0 | 3949.0 | 4949.0 | 5949.0 | 6949.0 |
| | 317 | 1000.0 | 2000.0 | 3000.0 | 4000.0 | 5000.0 | 6000.0 | 7000.0 |
| | 318 | 1000.0 | 2000.0 | 3000.0 | 4000.0 | 5000.0 | 6000.0 | 7000.0 |
| | 319 | 1000.0 | 2000.0 | 3000.0 | 4000.0 | 5000.0 | 6000.0 | 7000.0 |
| | 320 | 1000.0 | 2000.0 | 3000.0 | 4000.0 | 5000.0 | 6000.0 | 7000.0 |
| | 321 | 667.0 | 1667.0 | 2667.0 | 3667.0 | 4667.0 | 5667.0 | 6667.0 |
| | 322 | 507.0 | 1507.0 | 2507.0 | 3507.0 | 4507.0 | 5507.0 | 6507.0 |
| | 323 | 833.0 | 1833.0 | 2833.0 | 3833.0 | 4833.0 | 5833.0 | 6833.0 |
| | 324 | 1000.0 | 2000.0 | 3000.0 | 4000.0 | 5000.0 | 6000.0 | 7000.0 |
| 1955 | 325 | 920.0 | 1920.0 | 2920.0 | 3920.0 | 4920.0 | 5920.0 | 6920.0 |
| | 326 | 536.0 | 1536.0 | 2536.0 | 3536.0 | 4536.0 | 5536.0 | 6536.0 |
| | 327 | 260.0 | 1260.0 | 2260.0 | 3260.0 | 4260.0 | 5260.0 | 6260.0 |
| | 328 | 395.0 | 1395.0 | 2395.0 | 3395.0 | 4395.0 | 5395.0 | 6395.0 |
| | 329 | 635.0 | 1635.0 | 2635.0 | 3635.0 | 4635.0 | 5635.0 | 6635.0 |
| | 330 | 809.0 | 1809.0 | 2809.0 | 3809.0 | 4809.0 | 5809.0 | 6809.0 |



TABLE 4

| YEAR | MONTH 1 | C = 1000 | C = 2000 | C = 3000 | C = 4000 | C = 5000 | C = 6000 | C = 7000 |
|---|---|---|---|---|---|---|---|---|
| | 331 | 1000.0 | 2000.0 | 3000.0 | 4000.0 | 5000.0 | 6000.0 | 7000.0 |
| | 332 | 1000.0 | 2000.0 | 3000.0 | 4000.0 | 5000.0 | 6000.0 | 7000.0 |
| | 333 | 935.0 | 1935.0 | 2935.0 | 3935.0 | 4935.0 | 5935.0 | 6935.0 |
| | 334 | 852.0 | 1852.0 | 2852.0 | 3852.0 | 4852.0 | 5852.0 | 6852.0 |
| | 335 | 686.0 | 1686.0 | 2686.0 | 3686.0 | 4686.0 | 5686.0 | 6686.0 |
| | 336 | 445.0 | 1445.0 | 2445.0 | 3445.0 | 4445.0 | 5445.0 | 6445.0 |
| 1956 | 337 | 407.0 | 1407.0 | 2407.0 | 3407.0 | 4407.0 | 5407.0 | 6407.0 |
| | 338 | 592.0 | 1592.0 | 2592.0 | 3592.0 | 4592.0 | 5592.0 | 6592.0 |
| | 339 | 646.0 | 1646.0 | 2646.0 | 3646.0 | 4646.0 | 5646.0 | 6646.0 |
| | 340 | 672.0 | 1672.0 | 2672.0 | 3672.0 | 4672.0 | 5672.0 | 6672.0 |
| | 341 | 882.0 | 1882.0 | 2882.0 | 3882.0 | 4882.0 | 5882.0 | 6882.0 |
| | 342 | 1000.0 | 2000.0 | 3000.0 | 4000.0 | 5000.0 | 6000.0 | 7000.0 |
| | 343 | 1000.0 | 2000.0 | 3000.0 | 4000.0 | 5000.0 | 6000.0 | 7000.0 |
| | 344 | 955.0 | 1955.0 | 2955.0 | 3955.0 | 4955.0 | 5955.0 | 6955.0 |
| | 345 | 788.0 | 1788.0 | 2788.0 | 3788.0 | 4788.0 | 5788.0 | 6788.0 |
| | 346 | 800.0 | 1800.0 | 2800.0 | 3800.0 | 4800.0 | 5800.0 | 6800.0 |
| | 347 | 851.0 | 1851.0 | 2851.0 | 3851.0 | 4851.0 | 5851.0 | 6851.0 |
| | 348 | 809.0 | 1809.0 | 2809.0 | 3809.0 | 4809.0 | 5809.0 | 6809.0 |
| 1957 | 349 | 929.0 | 1929.0 | 2929.0 | 3929.0 | 4929.0 | 5929.0 | 6929.0 |
| | 350 | 1000.0 | 2000.0 | 3000.0 | 4000.0 | 5000.0 | 6000.0 | 7000.0 |
| | 351 | 972.0 | 1972.0 | 2972.0 | 3972.0 | 4972.0 | 5972.0 | 6972.0 |
| | 352 | 1000.0 | 2000.0 | 3000.0 | 4000.0 | 5000.0 | 6000.0 | 7000.0 |
| | 353 | 961.0 | 1961.0 | 2961.0 | 3961.0 | 4961.0 | 5961.0 | 6961.0 |
| | 354 | 662.0 | 1662.0 | 2662.0 | 3662.0 | 4662.0 | 5662.0 | 6662.0 |
| | 355 | 608.0 | 1608.0 | 2608.0 | 3608.0 | 4608.0 | 5608.0 | 6608.0 |
| | 356 | 667.0 | 1667.0 | 2667.0 | 3667.0 | 4667.0 | 5667.0 | 6667.0 |
| | 357 | 497.0 | 1497.0 | 2497.0 | 3497.0 | 4497.0 | 5497.0 | 6497.0 |
| | 358 | 438.0 | 1438.0 | 2438.0 | 3438.0 | 4438.0 | 5438.0 | 6438.0 |
| | 359 | 522.0 | 1522.0 | 2522.0 | 3522.0 | 4522.0 | 5522.0 | 6522.0 |
| | 360 | 719.0 | 1719.0 | 2719.0 | 3719.0 | 4719.0 | 5719.0 | 6719.0 |
| 1958 | 361 | 1000.0 | 2000.0 | 3000.0 | 4000.0 | 5000.0 | 6000.0 | 7000.0 |
| | 362 | 1000.0 | 2000.0 | 3000.0 | 4000.0 | 5000.0 | 6000.0 | 7000.0 |
| | 363 | 1000.0 | 2000.0 | 3000.0 | 4000.0 | 5000.0 | 6000.0 | 7000.0 |
| | 364 | 1000.0 | 2000.0 | 3000.0 | 4000.0 | 5000.0 | 6000.0 | 7000.0 |
| | 365 | 1000.0 | 2000.0 | 3000.0 | 4000.0 | 5000.0 | 6000.0 | 7000.0 |
| | 366 | 1000.0 | 2000.0 | 3000.0 | 4000.0 | 5000.0 | 6000.0 | 7000.0 |
| | 367 | 1000.0 | 2000.0 | 3000.0 | 4000.0 | 5000.0 | 6000.0 | 7000.0 |
| | 368 | 1000.0 | 2000.0 | 3000.0 | 4000.0 | 5000.0 | 6000.0 | 7000.0 |
| | 369 | 885.0 | 1885.0 | 2885.0 | 3885.0 | 4885.0 | 5885.0 | 6885.0 |
| | 370 | 893.0 | 1893.0 | 2893.0 | 3893.0 | 4893.0 | 5893.0 | 6893.0 |
| | 371 | 1000.0 | 2000.0 | 3000.0 | 4000.0 | 5000.0 | 6000.0 | 7000.0 |
| | 372 | 1000.0 | 2000.0 | 3000.0 | 4000.0 | 5000.0 | 6000.0 | 7000.0 |
| 1959 | 373 | 1000.0 | 2000.0 | 3000.0 | 4000.0 | 5000.0 | 6000.0 | 7000.0 |
| | 374 | 1000.0 | 2000.0 | 3000.0 | 4000.0 | 5000.0 | 6000.0 | 7000.0 |
| | 375 | 1000.0 | 2000.0 | 3000.0 | 4000.0 | 5000.0 | 6000.0 | 7000.0 |
| | 376 | 1000.0 | 2000.0 | 3000.0 | 4000.0 | 5000.0 | 6000.0 | 7000.0 |
| | 377 | 1000.0 | 2000.0 | 3000.0 | 4000.0 | 5000.0 | 6000.0 | 7000.0 |
| | 378 | 858.0 | 1858.0 | 2858.0 | 3858.0 | 4858.0 | 5858.0 | 6858.0 |



TABLE 4

TABLE 4

| YEAR | MONTH I | C = 1000 | C = 2000 | C = 3000 | C = 4000 | C = 5000 | C = 6000 | C = 7000 |
|---|---|---|---|---|---|---|---|---|
| | 379 | 1000.0 | 2000.0 | 3000.0 | 4000.0 | 5000.0 | 6000.0 | 7000.0 |
| | 380 | 1000.0 | 2000.0 | 3000.0 | 4000.0 | 5000.0 | 6000.0 | 7000.0 |
| | 381 | 841.0 | 1841.0 | 2841.0 | 3841.0 | 4841.0 | 5841.0 | 6841.0 |
| | 382 | 863.0 | 1863.0 | 2863.0 | 3863.0 | 4863.0 | 5863.0 | 6863.0 |
| | 383 | 919.0 | 1919.0 | 2919.0 | 3919.0 | 4919.0 | 5919.0 | 6919.0 |
| | 384 | 1000.0 | 2000.0 | 3000.0 | 4000.0 | 5000.0 | 6000.0 | 7000.0 |
| 1960 | 385 | 1000.0 | 2000.0 | 3000.0 | 4000.0 | 5000.0 | 6000.0 | 7000.0 |
| | 386 | 1000.0 | 2000.0 | 3000.0 | 4000.0 | 5000.0 | 6000.0 | 7000.0 |
| | 387 | 1000.0 | 2000.0 | 3000.0 | 4000.0 | 5000.0 | 6000.0 | 7000.0 |
| | 388 | 1000.0 | 2000.0 | 3000.0 | 4000.0 | 5000.0 | 6000.0 | 7000.0 |
| | 389 | 1000.0 | 2000.0 | 3000.0 | 4000.0 | 5000.0 | 6000.0 | 7000.0 |
| | 390 | 955.0 | 1955.0 | 2955.0 | 3955.0 | 4955.0 | 5955.0 | 6955.0 |
| | 391 | 907.0 | 1907.0 | 2907.0 | 3907.0 | 4907.0 | 5907.0 | 6907.0 |
| | 392 | 866.0 | 1866.0 | 2866.0 | 3866.0 | 4866.0 | 5866.0 | 6866.0 |
| | 393 | 872.0 | 1872.0 | 2872.0 | 3872.0 | 4872.0 | 5872.0 | 6872.0 |
| | 394 | 754.0 | 1754.0 | 2754.0 | 3754.0 | 4754.0 | 5754.0 | 6754.0 |
| | 395 | 970.0 | 1970.0 | 2970.0 | 3970.0 | 4970.0 | 5970.0 | 6970.0 |
| | 396 | 1000.0 | 2000.0 | 3000.0 | 4000.0 | 5000.0 | 6000.0 | 7000.0 |

Wahiawa Reservoir on Oahu and the Waita reservoir on Kauai with capacities of about 2900 mg. On Molokai the rubber-lined reservoir in the central plain of the island can hold 1400 mg. A capacity of only 1000 mg on the Kohala System would enhance water availability so greatly that the long term deficit would be only about one third of that expected of the system without storage.

The gains which would result from various storage capacities are put in perspective in the following summary of the statistical characteristics of the balance computations.

Storage Capacity (mg)

| | 1000 | 2000 | 3000 | 4000 | 5000 | 6000 | 7000 |
|---|---|---|---|---|---|---|---|
| Total remaining deficit (33 yrs.) | 9815 | 6392 | 3526 | 2272 | 1081 | 152 | 0 |
| Zero storage (mos) | 51 | 34 | 20 | 12 | 6 | 1 | 0 |
| Zero storage: % time | 12.9 | 8.6 | 5.1 | 3.0 | 1.5 | 0.3 | 0 |
| Zero storage: longest period (mos) | 8 | 7 | 7 | 4 | 3 | 1 | 0 |
| Zero storage: median period (mos) | 3 | 4 | 4 | 3 | 2 | 1 | 0 |
| Zero storage: minimum period (mos) | 1 | 2 | 2 | 2 | 1 | 1 | 0 |
| Zero storage: no. periods | 14 | 8 | 5 | 4 | 3 | 1 | 0 |
| Zero storage: % years | 42.4 | 24.2 | 15.2 | 12.1 | 9.1 | 3.0 | 0 |
| Spill-over(mos) | 93 | 67 | 53 | 50 | 47 | 40 | 40 |
| Spill-over: % time | 23.5 | 16.9 | 13.4 | 12.6 | 11.9 | 10.1 | 10.1 |

In table 2 (Historical model - deficit) the 33 yr. deficit of the demand model is given as 26,885 mg when no storage is provided. This deficit is sharply reduced by the addition of a relatively small storage capacity so that the cost of providing alternate sources of water, i.e. pumped groundwater, to supply remaining demand would be cut correspondingly. If groundwater delivered to the ditch level cost $100/mg, the 33 years saving with a 1000 mg reservoir would be $1,707,000, or an average of $51,727 per year. At higher storage capacities the savings would be greater.

Although a capacity of 6000 - 7000 mg would guarantee water at all times to satisfy the demand model, this capacity is by no means optimal. It is far too large for the benefits it would afford beyond those provided by smaller capacities. The reduction in deficit per 1000 mg capacity is greatest for low capacities, which means that the marginal cost of additional capacity will exceed the value of the reduced deficit at some point. The rate of reduction of the deficit per 1000 mg capacity is as follows:

| Capacity increase (mg) | | Deficit reduction (mg) |
|---|---|---|
| from | to | |
| 0 | 1000 | 17070 |
| 1000 | 2000 | 3423 |
| 2000 | 3000 | 2866 |
| 3000 | 4000 | 1254 |
| 4000 | 5000 | 1191 |
| 5000 | 6000 | 929 |
| 6000 | 7000 | 152 |

The rate of deficit reduction is, of course, greatest between zero storage and 1000 mg, but is also high between 1000 and 2000, and 2000 and 3000 mg. Beyond 3000 mg the rate drops so rapidly that it is not likely that increased investment in capacity could be justified by savings from the reduced deficit. The optimum storage capacity evidently lies between 1000 and 3000 mg.

Basal groundwater storage is an obvious alternative to surface storage, but high level dike water can also play a significant role in guaranteeing demand flows during dry seasons. Stored dike water can be used to supplement the stream flow in Honokane Nui during droughts. To give an example of how it could be programmed as an alternative to basal groundwater or surface storage, an examination was made of the historical record at Gage 7510 to determine the maximum cumulated deficit for consecutive months having less than average flow (gross average of 825 mg/mos.) and less than a flow of 600 mg/mos. For the case of the gross average flow the maximum cumulated deficit was 1845 mg, while for the fixed 600 mg/mos. flow the maximum was 730 mg. The Koelling Tunnel (see Phase II Report and a later section on the tunnel in this report) had an initial storage of greater than 5000 mg, far more than adequate to satisfy a fixed flow of 825 mg/mos. throughout the deficit period if it could be extracted from the dike compartments at continuous high rates. However, even if the tunnel were bulkheaded to its original storage condition, the rate of flow from storage might not be able to make up the monthly deficits toward the end of a persistent dry period.

The maximum deficit for the less than 825 mg/mos. flows accumulated over a series of ten months. Were the Koelling Tunnel at its initial storage, the free release of water over 300 days would be (see Phase II report and the amendment on tunnels in this report):

$$V_s = \frac{4.6 \{1 - \exp. ([-.00123] [300])\}}{.00123} = 1154 \text{ mg}$$

which is 63% of the deficit. Once developed high level dike water requires no man-made energy for delivery and therefore it would be extremely valuable, even though it might not be adequate to solve all deficiency problems.

For a fixed flow of 600 mg/mos. the maximum deficit of 730 mg accumulated over 5 months. The volume supplied over this period of time from the hypothetical original condition of Koelling Tunnel would be 630 mg, 86% of the cumulated deficit.

Percentile Model (Deficit - Surplus)

The percentile model is included to help visualize the probabilistic nature of the occurrence of flows. Actually the statistics of this model are included in the flow duration curves given in the Phase II Report, and the digital tabulation by 5% time intervals of the historical flows in table 5 merely expresses the .05 probability of occurrence of these flows.

TABLE 5
PERCENTILE MODEL
KOHALA DITCH - POLOLU GAGE 7510
Q IN 5% INTERVALS FLOW DURATION
(FLOW IN MG/MONTH)
1928 - 1960

| % TILE RANGE | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 100-95 | 492 | 320 | 454 | 637 | 680 | 635 | 603 | 554 | 351 | 310 | 495 | 412 |
| 95-90 | 533 | 444 | 495 | 743 | 720 | 669 | 680 | 620 | 418 | 385 | 510 | 480 |
| 90-85 | 565 | 507 | 575 | 768 | 753 | 704 | 745 | 700 | 482 | 470 | 530 | 557 |
| 85-80 | 598 | 538 | 625 | 790 | 780 | 733 | 808 | 777 | 527 | 530 | 553 | 637 |
| 80-75 | 623 | 563 | 675 | 810 | 811 | 758 | 861 | 834 | 654 | 566 | 578 | 690 |
| 75-70 | 648 | 588 | 725 | 830 | 839 | 779 | 889 | 870 | 673 | 599 | 620 | 724 |
| 70-65 | 667 | 607 | 775 | 846 | 859 | 794 | 908 | 897 | 685 | 622 | 668 | 757 |
| 65-60 | 681 | 621 | 822 | 856 | 875 | 807 | 919 | 910 | 697 | 642 | 701 | 781 |
| 60-55 | 694 | 636 | 854 | 866 | 892 | 819 | 943 | 922 | 709 | 662 | 718 | 793 |
| 55-50 | 715 | 650 | 874 | 877 | 910 | 832 | 972 | 932 | 723 | 681 | 728 | 802 |
| 50-45 | 737 | 668 | 893 | 888 | 929 | 849 | 995 | 943 | 740 | 700 | 744 | 812 |
| 45-40 | 756 | 690 | 907 | 901 | 947 | 871 | 1033 | 953 | 757 | 721 | 760 | 822 |
| 40-35 | 775 | 716 | 919 | 918 | 968 | 895 | 1079 | 967 | 771 | 750 | 779 | 832 |
| 35-30 | 798 | 755 | 932 | 938 | 993 | 924 | 1110 | 989 | 785 | 778 | 815 | 853 |
| 30-25 | 823 | 790 | 945 | 964 | 1020 | 960 | 1133 | 1016 | 807 | 796 | 880 | 905 |
| 25-20 | 851 | 810 | 960 | 1004 | 1051 | 1004 | 1157 | 1050 | 834 | 810 | 944 | 960 |
| 20-15 | 884 | 830 | 985 | 1047 | 1089 | 1047 | 1180 | 1103 | 857 | 824 | 984 | 1015 |
| 15-10 | 925 | 865 | 1045 | 1083 | 1132 | 1083 | 1203 | 1170 | 876 | 842 | 1020 | 1075 |
| 10- 5 | 985 | 965 | 1113 | 1130 | 1170 | 1135 | 1226 | 1250 | 896 | 870 | 1048 | 1139 |
| 5- 0 | 1040 | 1030 | 1165 | 1195 | 1204 | 1230 | 1249 | 1383 | 926 | 910 | 1068 | 1259 |

TABLE 5

Table 6 shows the deficits by 5% intervals relative to the Alexander demand model, and table 7 the corollary surpluses. The listed deficits and surpluses have a .05, or 1 year in 20 years, chance of occurring. The deficit and surplus probabilities for each month may be summarized as follows:

| | Expectation that a deficit will occur | Expectation that a surplus will occur |
|---|---|---|
| January | .25 | .75 |
| February | .40 | .60 |
| March | .30 | .70 |
| April | .15 | .85 |
| May | .45 | .50 |
| June | .70 | .30 |
| July | .45 | .55 |
| August | .70 | .30 |
| September | .95 | .05 |
| October | .70 | .25 |
| November | .35 | .65 |
| December | .15 | .85 |

These statistics are a tautological restatement of plantation experience that the expectancy of water deficits are lowest from November through April except for the relatively high deficit probability exhibited for February, which climatologically is also unusual in that its rainfall is among the lowest of the months. The probability of experiencing a deficit is nearly certain in September, and also likely in June, August and October. It is evident from the statistics, and unambiguously certain from experience, that the late summer and early fall months are when a need for supplementary water is most desperately felt. On the other hand the month of July, when orographic showers are frequent in the mountains, has a deficit expectancy of only .45.

TABLE 6
PERCENTILE MODEL (DEFICIT)
KOHALA DITCH - POLOLU GAGE 7510
Q IN 5% INTERVALS FLOW DURATION
(DEFICIT IN MG/MONTH)
1928 - 1960

| % TILE RANGE | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| DEMAND | 628 | 626 | 744 | 788 | 910 | 946 | 969 | 1001 | 905 | 796 | 694 | 617 |
| 100-95 | 136 | 306 | 290 | 151 | 230 | 311 | 366 | 447 | 554 | 486 | 199 | 205 |
| 95-90 | 95 | 182 | 249 | 45 | 190 | 277 | 289 | 381 | 487 | 411 | 184 | 137 |
| 90-85 | 63 | 119 | 169 | 20 | 157 | 242 | 224 | 301 | 423 | 326 | 164 | 60 |
| 85-80 | 30 | 88 | 119 | | 130 | 213 | 161 | 224 | 378 | 266 | 141 | |
| 80-75 | 5 | 63 | 69 | | 99 | 188 | 108 | 167 | 251 | 230 | 116 | |
| 75-70 | | 38 | 19 | | 71 | 167 | 80 | 131 | 232 | 197 | 74 | |
| 70-65 | | 19 | | | 51 | 152 | 61 | 104 | 220 | 174 | 26 | |
| 65-60 | | 5 | | | 35 | 139 | 50 | 91 | 208 | 154 | | |
| 60-55 | | | | | 18 | 127 | 26 | 79 | 196 | 134 | | |
| 55-50 | | | | | | 114 | | 69 | 182 | 115 | | |
| 50-45 | | | | | | 97 | | 58 | 165 | 96 | | |
| 45-40 | | | | | | 75 | | 48 | 148 | 75 | | |
| 40-35 | | | | | | 51 | | 34 | 134 | 46 | | |
| 35-30 | | | | | | 22 | | 12 | 120 | 18 | | |
| 30-25 | | | | | | | | | 98 | | | |
| 25-20 | | | | | | | | | 71 | | | |
| 20-15 | | | | | | | | | 48 | | | |
| 15-10 | | | | | | | | | 29 | | | |
| 10- 5 | | | | | | | | | 9 | | | |
| 5- 0 | | | | | | | | | | | | |

TABLE 6

TABLE 7
PERCENTILE MODEL (SURPLUS)
KOHALA DITCH - POLOLU GAGE 7510
Q IN 5% INTERVALS FLOW DURATION
(SURPLUS IN MG/MONTH)
1928 - 1960

| % TILE RANGE | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| DEMAND | 628 | 626 | 744 | 788 | 910 | 946 | 969 | 1001 | 905 | 796 | 694 | 617 |
| 100-95 | | | | | | | | | | | | |
| 95-90 | | | | | | | | | | | | |
| 90-85 | | | | | | | | | | | | |
| 85-80 | | | | 2 | | | | | | | | 20 |
| 80-75 | | | | 22 | | | | | | | | 73 |
| 75-70 | 20 | | | 42 | | | | | | | | 107 |
| 70-65 | 39 | | 31 | 58 | | | | | | | | 140 |
| 65-60 | 53 | | 78 | 68 | | | | | | | 7 | 164 |
| 60-55 | 66 | 10 | 110 | 78 | | | | | | | 24 | 176 |
| 55-50 | 87 | 24 | 130 | 89 | | | 3 | | | | 34 | 185 |
| 50-45 | 109 | 42 | 149 | 100 | 19 | | 26 | | | | 50 | 195 |
| 45-40 | 128 | 64 | 163 | 113 | 37 | | 64 | | | | 66 | 205 |
| 40-35 | 147 | 90 | 175 | 130 | 58 | | 110 | | | | 85 | 215 |
| 35-30 | 170 | 129 | 188 | 150 | 83 | | 141 | | | | 121 | 236 |
| 30-25 | 195 | 164 | 201 | 176 | 110 | 14 | 164 | 15 | | | 186 | 288 |
| 25-20 | 223 | 184 | 216 | 216 | 141 | 58 | 188 | 49 | | 14 | 250 | 343 |
| 20-15 | 256 | 204 | 241 | 259 | 179 | 101 | 211 | 102 | | 28 | 290 | 398 |
| 15-10 | 297 | 239 | 301 | 295 | 222 | 137 | 234 | 169 | | 46 | 326 | 458 |
| 10- 5 | 357 | 339 | 369 | 342 | 260 | 189 | 257 | 249 | | 74 | 354 | 522 |
| 5- 0 | 412 | 404 | 421 | 407 | 294 | 284 | 280 | 382 | 21 | 114 | 374 | 642 |

TABLE 7

Synthetic Hydrology Model

The historical record provides flow data for a short interval in the possible life of a transmission system, whether it is a stream, tunnel or ditch, and cannot be expected to incorporate the total range of flow over all possible time. The usefulness of the historical record can be extended, however, by using its statistical moments to generate new flow series. The most common generating scheme is the lag-1 Markov model which, for normally distributed flows, needs only the population mean, variance and first order correlation coefficient. The monthly flows at Gage 7510 are essentially normally distributed and therefore can be extended with a comparatively tractable version of the lag-1 model.

The lag-1 model assumes that a flow is affected only by the immediate preceding flow. If still earlier flows affect the flow in question, more than one lag must be computed and computational effort becomes formidable. In Hawaii streams respond quickly to rainfall and in any month both the base flow and very high stages are likely to be recorded, so that at most only the lag-1 assumption is justifiable. Actually stream flows greater than base flow reflect immediate rainfall, which means that the lag-1 correlation coefficients of the model serve also to connect rainfall dependency between succeeding months.

In the generating scheme the flow of each month is correlated with the flow of the preceding month to obtain the lag-1 correlation coefficient. Table 8 lists these coefficients along with other relevant statistical parameters. The strongest correlations ($r > .5$) exist between February and January, June and May, August and July, September and August, October and September, November and October, and December and November. The correlation between August and July ($r = .75$) is especially strong, and a strong correlation continues in the sequence of months from August through December. As a practical rule of thumb, if July provides less than normal flows as a result of drought, similar flows are expectable for the reminder of the year.

Except between February and January, and December and November, the winter and spring months correlate poorly with their immediate predecessors ($r < .5$). Also, the correlation between July and June is extremely poor ($r = .06$) and therefore it is not reasonable to predict a lengthy dry or wet spell for summer and fall until the July flows are measured. If judiciously used, the correlation coefficients in conjunction with other statistical parameters may serve as a management tool.

With the data in table 8 and standard normal deviates computed by the Box-Muller method, a 1200 months (100 years) series of flows was generated on the Wang Computer provided by Akinaka and Associates, Ltd. The print-out of the standard normal deviates (mean= 0, standard deviation=1) is given as table 9.

Table 8

Statistical Parameters of Flows at Gage 7510 for the Period

1928 through 1960. Flow Units in Million Gallons per Month.

| Month (j) | Mean Flow $\bar{q}_j$ | Std. Dev. $s_j$ | Coeff. Var. $c_j$ | $a^{(1)}$ | $b^{(1)}$ | Coeff. Corr. $r_{j,j-1}$ | Std. Error $s_{j,j-1}$ |
|---|---|---|---|---|---|---|---|
| Jan. | 746 | 156 | .209 | 169.4 | .68 | .29 | 152 |
| Feb. | 677 | 177 | .261 | 636.2 | .30 | .60 | 144 |
| Mar. | 838 | 185 | .221 | 781.2 | .15 | .28 | 180 |
| April | 907 | 146 | .161 | 705.1 | .25 | .19 | 146 |
| May | 930 | 145 | .156 | 265.8 | .65 | .25 | 143 |
| June | 874 | 175 | .200 | 426.3 | .07 | .54 | 149 |
| July | 984 | 190 | .193 | 173.9 | .80 | .06 | 193 |
| Aug. | 959 | 203 | .212 | 411.5 | .34 | .75 | 137 |
| Sept. | 729 | 125 | .172 | 115.1 | .77 | .55 | 106 |
| Oct. | 676 | 159 | .235 | 303.5 | .67 | .60 | 131 |
| Nov. | 758 | 181 | .239 | 219.0 | .79 | .59 | 149 |
| Dec. | 817 | 205 | .251 | 563.7 | .22 | .70 | 149 |

1. $a$ is the intercept value and $b$ the slope in the regression equation: $\bar{q}_j = a + b\,\bar{q}_{j-1}$

TABLE 9

SYNTHETIC MODEL
RANDOM NUMBER GENERATOR
KOHALA DITCH - POLOLU GAUGE 7510

INPUT:
m = 0.000
s = 1.000
Ua = .300
Ub = .200

| YEAR | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | .479 | 1.475 | -.807 | 1.338 | -.817 | -.047 | -1.153 | -1.192 | .305 | 1.080 | -1.226 | -1.915 |
| 2 | -.088 | -.288 | 1.096 | -.364 | 2.042 | -.993 | -.841 | .755 | .684 | -.142 | -.172 | .425 |
| 3 | 1.615 | .547 | -1.741 | -1.378 | -.516 | .502 | 1.787 | .629 | -1.081 | -1.608 | -2.462 | -.202 |
| 4 | -.654 | -1.032 | -.753 | .997 | -1.515 | -.821 | -1.855 | -.051 | 1.107 | .430 | -.166 | .020 |
| 5 | -.409 | .907 | 2.539 | -.934 | 1.061 | -.189 | .123 | -.073 | -.088 | 1.449 | -.024 | 1.610 |
| 6 | -.913 | -1.423 | .241 | .306 | .106 | -.299 | -.686 | -.449 | .536 | -.683 | .045 | -.249 |
| 7 | 1.014 | .340 | -1.851 | .084 | .084 | .812 | 2.448 | 1.319 | .353 | -.081 | -.726 | -.186 |
| 8 | .942 | .355 | -1.200 | -.535 | -.203 | .499 | 2.592 | .879 | -.871 | -.421 | .559 | .539 |
| 9 | .062 | -.506 | -.938 | -1.025 | -.247 | 1.168 | -.785 | .395 | 1.321 | .730 | -1.255 | 1.227 |
| 10 | -1.513 | -.158 | -.116 | -.224 | 1.612 | -.229 | -.534 | .493 | -.440 | -1.135 | -.169 | .178 |
| 11 | -1.765 | .911 | -.011 | .418 | .011 | 1.150 | -1.082 | -1.687 | .912 | 1.593 | -1.008 | -.197 |
| 12 | .663 | 1.191 | 1.189 | .046 | -1.057 | -.812 | .020 | 1.354 | .055 | .234 | -.624 | -1.240 |
| 13 | -1.590 | .471 | -.836 | -1.031 | -.138 | .802 | -.793 | -.848 | -1.195 | .645 | .291 | -.330 |
| 14 | -1.486 | .218 | .366 | -.354 | -1.205 | 1.430 | 1.679 | .076 | -.512 | -.080 | -.715 | .391 |
| 15 | .029 | .791 | .866 | 1.308 | -.814 | -1.587 | -1.115 | .626 | -.741 | -1.347 | .877 | -.569 |
| 16 | .089 | -.136 | .637 | -1.500 | -1.204 | .809 | .050 | .197 | .652 | -1.036 | -.514 | -.741 |
| 17 | -.258 | -.862 | -.680 | -1.370 | 1.249 | .172 | -.699 | -1.227 | -1.209 | .012 | -.048 | .316 |
| 18 | 2.740 | .523 | -.801 | .211 | 1.385 | -2.545 | 1.339 | .586 | -1.533 | -.689 | .892 | .606 |
| 19 | -.213 | -.531 | -.350 | .795 | -.317 | .731 | 1.237 | .704 | .354 | -.462 | -.378 | -.229 |
| 20 | 1.167 | -.674 | .017 | -.866 | -.539 | 1.438 | -.726 | -.479 | -.532 | .738 | 1.345 | -.577 |
| 21 | -.813 | -.263 | .807 | -.464 | -.574 | 1.099 | -.988 | .028 | 1.089 | -.656 | .247 | -.793 |
| 22 | -1.244 | -1.914 | .396 | -.977 | -.097 | 1.599 | .885 | -.389 | -.482 | .348 | -.168 | -.766 |
| 23 | .742 | .525 | -1.013 | -1.389 | .613 | .699 | .525 | 1.165 | -.994 | -.111 | .459 | -2.054 |
| 24 | -.892 | -.521 | -.910 | .475 | -.661 | -.886 | -1.635 | -.044 | -.380 | .759 | -.234 | -.659 |
| 25 | -.501 | 1.697 | -.626 | 1.464 | -.524 | .648 | .676 | .659 | -.296 | -.695 | -1.080 | .191 |
| 26 | -1.407 | -.253 | .499 | -1.098 | .794 | .444 | .575 | .322 | .504 | 1.167 | .149 | -.242 |
| 27 | -1.263 | -2.134 | 2.069 | .238 | -.738 | -1.324 | -1.873 | .051 | -1.081 | .540 | .325 | -1.130 |
| 28 | .712 | .473 | -.445 | 2.294 | .089 | -.993 | -.831 | .412 | -.560 | .092 | 1.000 | 1.648 |
| 29 | -.014 | -.601 | -.245 | .854 | 1.710 | .350 | -.948 | .239 | .279 | -.092 | .416 | -1.189 |
| 30 | .306 | -.513 | -.380 | .790 | .925 | -1.124 | -.633 | 1.415 | -.930 | .632 | -.478 | -.192 |
| 31 | 1.130 | .542 | .280 | -.069 | -.771 | -1.699 | -.536 | -.171 | .465 | .192 | -.283 | -.174 |
| 32 | -1.524 | .548 | -.391 | 1.005 | -.322 | -.514 | .660 | -.483 | .657 | -1.168 | .619 | .228 |
| 33 | -.206 | 1.270 | 1.696 | -.095 | -1.174 | .065 | .883 | .737 | .007 | -.588 | -1.502 | -.876 |
| 34 | -1.094 | -1.020 | .764 | .100 | -1.017 | 1.237 | -.939 | -.238 | .356 | .225 | 1.137 | -1.353 |
| 35 | 1.760 | .357 | .519 | -1.055 | .716 | -1.178 | .616 | .044 | .117 | 1.636 | .368 | -1.087 |
| 36 | .015 | -.752 | -1.234 | .814 | .503 | 1.445 | .492 | .229 | -.015 | .345 | -.374 | -.555 |
| 37 | -1.626 | -.979 | -.152 | -.874 | 1.756 | -.607 | .871 | 1.639 | 1.529 | -.675 | -1.110 | 2.090 |
| 38 | -.190 | .682 | 1.434 | 1.245 | .432 | .980 | 1.354 | -.737 | -.452 | -.185 | 1.579 | .203 |
| 39 | -.258 | -.020 | .751 | .802 | .014 | .870 | .787 | -.221 | .399 | 1.259 | -.199 | -1.030 |

TABLE 9

| YEAR | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 40 | -1.593 | .326 | .047 | 1.897 | -.288 | -.195 | 1.755 | -.634 | .277 | -.535 | -.141 | -.161 |
| 41 | .167 | .243 | -1.365 | -1.029 | -.537 | .471 | 1.374 | .044 | -2.560 | .674 | -.640 | -.901 |
| 42 | -.313 | 1.887 | -1.095 | -.035 | .492 | 1.754 | -1.182 | .772 | .089 | .872 | 1.291 | .521 |
| 43 | -1.140 | -.453 | -.643 | -1.490 | -.176 | -.104 | .144 | .673 | 1.002 | -.149 | .396 | 1.616 |
| 44 | -.177 | -.405 | -.604 | -.812 | -.593 | -.202 | .376 | -.052 | 2.189 | 1.350 | .223 | -.525 |
| 45 | -.271 | -.710 | .682 | 1.188. | -.331 | 1.090 | 1.034 | -.563 | -1.310 | .395 | .316 | -.268 |
| 46 | .079 | -.293 | .204 | .117 | -.301 | -.042 | -1.553 | -.364 | -1.157 | -1.291 | .016 | -1.222 |
| 47 | -.372 | .342 | -1.180 | .353 | -.961 | -.998 | 2.045 | 1.028 | .159 | -1.170 | -.681 | -.823 |
| 48 | -1.793 | -.644 | -1.102 | -.491 | 1.321 | -1.294 | 2.399 | 1.572 | -.804 | .675 | .625 | -.057 |
| 49 | 1.458 | -1.899 | .855 | -.094 | -1.868 | 1.515 | -.781 | -.870 | -1.082 | -.068 | 1.827 | .550 |
| 50 | -.652 | -.852 | .249 | .897 | .501 | -1.189 | -.415 | .295 | 3.143 | 1.351 | 1.881 | -.993 |
| 51 | -2.660 | -.691 | -.360 | 1.093 | -.537 | -.944 | .184 | .573 | -1.955 | -.324 | -.705 | 1.641 |
| 52 | .837 | -.442 | 1.020 | .939 | -.020 | -.766 | .758 | -.741 | -.098 | -.156 | .382 | -.673 |
| 53 | .677 | .945 | -.204 | 1.288 | -.746 | .448 | -1.094 | 1.651 | 1.369 | .214 | 2.577 | .214 |
| 54 | 2.435 | -1.049 | -.134 | -.506 | -.179 | 2.315 | -1.144 | 1.842 | -1.028 | 1.528 | -.117 | 1.398 |
| 55 | -.441 | -.303 | -.405 | .226 | -.013 | 2.035 | -.425 | -1.882 | -.180 | .044 | -.628 | .657 |
| 56 | -1.693 | .452 | 1.251 | -.171 | -.546 | .777 | -.051 | -1.438 | -.931 | .398 | 1.172 | -.163 |
| 57 | -.037 | -.792 | .992 | .246 | .454 | -.350 | 1.380 | .481 | .469 | .616 | .132 | -.077 |
| 58 | -.048 | .191 | .972 | -.066 | -.788 | 2.050 | -.057 | -.024 | .265 | .352 | -1.029 | .766 |
| 59 | .629 | 1.176 | -.104 | -.909 | -.146 | .441 | -.484 | -1.488 | .834 | -.420 | -2.036 | -.105 |
| 60 | .277 | -.086 | -.815 | .137 | 1.474 | .304 | .479 | .897 | .928 | .173 | .031 | 1.082 |
| 61 | -.730 | .546 | -1.911 | -.822 | -.988 | 2.355 | .286 | .521 | 1.290 | -.495 | -1.773 | 2.355 |
| 62 | -1.020 | .271 | .045 | .251 | .586 | .202 | .197 | .991 | -1.339 | -.391 | .929 | -.797 |
| 63 | -.335 | .686 | -.086 | .616 | -.297 | -.340 | .383 | -.941 | .312 | .654 | 1.392 | 1.729 |
| 64 | -.260 | .585 | 1.013 | .350 | .148 | -1.221 | .502 | 1.155 | .292 | .453 | -1.129 | -.168 |
| 65 | .641 | -.176 | -1.321 | -.318 | .657 | -.811 | .165 | -.003 | .399 | .319 | 1.530 | .006 |
| 66 | 1.239 | 1.637 | 1.903 | .378 | .135 | .519 | -1.562 | -.507 | -.763 | -.966 | -.258 | -.396 |
| 67 | 1.373 | -1.080 | -.289 | 1.286 | .196 | -.363 | .295 | -.830 | .308 | -1.684 | -.955 | -.595 |
| 68 | 1.997 | -1.023 | 1.411 | -1.313 | .026 | -.508 | -.778 | -.577 | .817 | -.033 | -.196 | 1.117 |
| 69 | 1.269 | .071 | 1.050 | -1.171 | -.508 | .463 | .368 | -1.163 | .401 | .011 | .789 | .417 |
| 70 | -1.345 | 1.022 | -2.035 | -1.067 | .363 | .317 | -.700 | -1.536 | .579 | 1.353 | -.785 | .367 |
| 71 | .125 | .754 | -1.081 | -.494 | -.128 | -1.439 | .565 | -.455 | -.748 | -.622 | .154 | -.478 |
| 72 | 2.435 | .448 | -.630 | 2.433 | 1.062 | -.657 | -.073 | -.225 | .299 | .635 | .446 | -.040 |
| 73 | -.668 | .305 | -1.312 | .447 | .171 | -.439 | .925 | .571 | .342 | -.150 | .741 | -.710 |
| 74 | .150 | -.151 | 1.282 | -.944 | -.290 | -.343 | .126 | -.668 | -.687 | -.337 | 1.449 | -.344 |
| 75 | -.341 | 1.675 | -.522 | .450 | -2.704 | 1.955 | -.511 | 1.611 | -1.087 | .631 | .076 | -1.168 |
| 76 | -1.463 | 2.100 | -.511 | 2.074 | -.165 | .439 | .861 | .227 | 1.898 | -.240 | -.810 | -.059 |
| 77 | -.833 | .079 | -.003 | .181 | 1.377 | -1.624 | -.334 | .324 | .269 | 2.169 | -.417 | -1.742 |
| 78 | -.839 | .184 | -.693 | -.174 | -.224 | .184 | 1.471 | -.345 | -2.430 | 1.268 | -1.663 | .447 |
| 79 | .317 | -1.781 | -.156 | .236 | 1.439 | 1.142 | .270 | .739 | -1.278 | .864 | -.642 | .640 |
| 80 | .296 | -1.190 | -.785 | 1.449 | .031 | -.921 | .393 | .124 | .527 | .067 | -.049 | 1.070 |
| 81 | -.054 | -.094 | -.924 | .384 | -1.209 | -1.227 | -1.114 | -1.191 | 1.040 | .669 | .472 | 1.445 |
| 82 | -1.072 | -.723 | 1.787 | .297 | -.431 | .053 | -1.546 | .461 | -.496 | -.254 | .801 | .120 |
| 83 | .713 | -.541 | -.356 | .966 | .388 | .395 | .425 | 1.786 | -.709 | -.269 | -.137 | -2.343 |
| 84 | .209 | 1.536 | -1.111 | -.451 | .996 | .888 | 1.084 | .277 | -.588 | 1.327 | 1.720 | -.180 |
| 85 | .325 | .085 | .077 | -.318 | 2.055 | -1.159 | 1.190 | .671 | -.713 | -.646 | .488 | .772 |
| 86 | -.525 | -.171 | .316 | .116 | -.479 | -.307 | 1.734 | .343 | -1.024 | -.298 | .767 | 1.734 |
| 87 | .013 | -1.747 | -.517 | .600 | .109 | -2.736 | 1.083 | -.304 | 1.557 | .854 | -.028 | .911 |
| 88 | .993 | -2.598 | 1.744 | -.061 | -1.518 | .398 | -.742 | .571 | -.231 | .368 | -1.403 | -.929 |

TABLE 9

| YEAR | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 89 | .174 | -2.221 | -.684 | -.502 | -.157 | -.130 | 1.063 | -1.251 | -1.315 | -.078 | .499 | -.281 |
| 90 | -.407 | -.719 | -.746 | .684 | -.755 | -1.328 | -1.652 | .495 | .795 | .003 | -1.599 | -.406 |
| 91 | -.854 | 2.073 | .122 | -.897 | 1.389 | -.599 | -1.443 | -.787 | -1.416 | -.882 | .603 | 1.323 |
| 92 | -.671 | -1.681 | .489 | .950 | -.311 | .170 | -1.198 | -.232 | .807 | .446 | -.133 | -.177 |
| 93 | -1.562 | -.685 | -.004 | .675 | -.300 | -1.237 | .203 | -.588 | -.251 | -.392 | -.785 | .027 |
| 94 | -.534 | 1.130 | -.989 | -1.555 | 1.144 | -.424 | -1.320 | -.791 | -.360 | .633 | -.430 | 1.578 |
| 95 | 2.300 | 1.224 | -1.134 | .022 | -.574 | -.989 | -.481 | 1.265 | -1.349 | -.660 | -.590 | -2.040 |
| 96 | 1.078 | -.350 | 1.914 | -1.902 | -.467 | -.168 | 1.905 | .452 | .975 | .577 | -.384 | 1.006 |
| 97 | 1.996 | -1.224 | .924 | .999 | .459 | .779 | .113 | .677 | .816 | 1.524 | -.116 | -1.379 |
| 98 | -2.244 | -.361 | .543 | -1.025 | -.653 | -.501 | 1.083 | 1.348 | 1.302 | -.688 | 1.435 | -.029 |
| 99 | .179 | -.181 | -1.330 | .959 | .035 | -.078 | 1.105 | .041 | 1.262 | -1.392 | 1.639 | 1.545 |
| 100 | .043 | .293 | .818 | .137 | -.151 | -.423 | -.566 | .699 | .326 | .077 | .069 | .021 |



TABLE 9

Table 10 is a print-out of the 100 years of simulated flows computed by the Markobv lag-1 model. These flows belong to a different time series set than the historical flows and theoretically could occur as tabulated if the life of the system were infinitely long and the flow process were stationary, that is, the statistical parameters describing flow frequencies remained constant over time. A comparison of interest between the historical and simulated records is the lowest flow noted for each month, which are as follows (flows in million gallons):

| | Jan. | Feb. | Mar. | Apr. | May | June |
|---|---|---|---|---|---|---|
| Lowest historical flow | 463 | 242 | 468 | 543 | 660 | 619 |
| Lowest lag-1 flow | 377 | 267 | 495 | 656 | 630 | 399 |
| Difference | 86 | 25 | 27 | 113 | 30 | 220 |

| | July | Aug. | Sept. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|
| Lowest historical flow | 566 | 527 | 317 | 280 | 512 | 376 |
| Lowest lag-1 flow | 558 | 567 | 482 | 373 | 271 | 350 |
| Difference | 8 | 40 | 165 | 93 | 241 | 26 |

In six of the months (Jan., May, June, July, Nov., Dec.) the simulated 100 year low flow is less than historically recorded; in the other six months (Feb., March, April, Aug., Sept., Oct.) experienced low flows are less than the 100 year computed values. The months of June, September and November show significant differences between historical and simulated low flows, but the other months show reasonably close fits. It is possible that some of the very low historical flows reflect ditch maintenance operations when water was diverted from the system before reaching Gage 7510. The low simulated flows suggest that in at least six months of the year the

TABLE 10

SYNTHETIC MODEL
100 YEAR FLOW SIMULATION
KOHALA DITCH - POLOLU GAUGE 7510
(FLOW IN MG/MONTH)

| YEAR | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 805.8 | 946.7 | 744.9 | 1077.9 | 921.9 | 865.0 | 831.8 | 667.4 | 651.8 | 756.8 | 663.8 | 410.2 |
| 2 | 549.2 | 565.4 | 1014.9 | 819.6 | 1132.4 | 715.1 | 748.8 | 948.8 | 793.6 | 706.1 | 759.7 | 901.0 |
| 3 | 985.9 | 846.2 | 555.2 | 656.2 | 732.5 | 947.5 | 1268.5 | 1233.0 | 722.0 | 464.2 | 270.9 | 617.3 |
| 4 | 573.1 | 446.6 | 655.3 | 1011.9 | 801.3 | 721.1 | 626.4 | 740.1 | 758.8 | 753.6 | 798.4 | 834.2 |
| 5 | 702.7 | 817.5 | 1327.1 | 871.4 | 1040.4 | 848.8 | 978.9 | 943.6 | 714.4 | 851.0 | 894.3 | 1177.8 |
| 6 | 796.7 | 451.3 | 837.0 | 950.0 | 966.1 | 824.3 | 857.3 | 808.3 | 727.0 | 586.8 | 692.8 | 746.6 |
| 7 | 840.5 | 764.8 | 519.1 | 856.0 | 912.9 | 1014.6 | 1406.2 | 1430.8 | 938.6 | 822.8 | 781.1 | 787.9 |
| 8 | 850.3 | 770.5 | 633.4 | 791.9 | 843.4 | 954.9 | 1375.7 | 1338.2 | 782.0 | 661.6 | 818.9 | 942.8 |
| 9 | 811.2 | 611.7 | 654.5 | 725.8 | 802.6 | 1068.9 | 1043.9 | 1061.3 | 898.9 | 897.3 | 772.0 | 1062.4 |
| 10 | 669.1 | 625.7 | 806.6 | 869.0 | 1106.4 | 846.7 | 894.5 | 990.1 | 696.4 | 505.7 | 600.3 | 800.1 |
| 11 | 518.0 | 759.4 | 852.3 | 968.9 | 964.6 | 1077.5 | 1013.7 | 690.3 | 721.0 | 874.5 | 785.8 | 787.3 |
| 12 | 815.9 | 901.6 | 1093.6 | 964.9 | 832.0 | 725.0 | 865.2 | 1118.8 | 793.5 | 754.5 | 739.8 | 567.5 |
| 13 | 433.6 | 657.9 | 682.2 | 730.4 | 818.3 | 1006.1 | 991.8 | 819.7 | 557.9 | 630.4 | 759.3 | 752.5 |
| 14 | 531.0 | 645.9 | 898.3 | 868.7 | 762.4 | 1111.7 | 1388.6 | 1209.7 | 770.4 | 696.7 | 682.0 | 868.8 |
| 15 | 773.3 | 820.2 | 1023.8 | 1128.6 | 949.4 | 598.1 | 619.0 | 850.7 | 614.8 | 417.3 | 665.2 | 674.7 |
| 16 | 692.2 | 636.6 | 945.6 | 716.1 | 680.6 | 997.3 | 1090.7 | 1055.2 | 829.8 | 618.6 | 645.7 | 634.6 |
| 17 | 630.4 | 493.7 | 677.9 | 681.6 | 961.6 | 906.4 | 922.4 | 714.6 | 517.7 | 519.1 | 626.7 | 836.0 |
| 18 | 1096.7 | 878.2 | 732.3 | 915.9 | 1103.8 | 441.9 | 800.4 | 950.5 | 572.5 | 470.0 | 709.1 | 920.0 |
| 19 | 766.3 | 593.1 | 757.6 | 1003.6 | 943.0 | 1002.7 | 1244.4 | 1231.5 | 865.1 | 718.7 | 743.1 | 767.1 |
| 20 | 868.9 | 601.5 | 826.1 | 782.1 | 797.1 | 1115.6 | 1089.4 | 939.6 | 668.5 | 725.4 | 971.3 | 773.7 |
| 21 | 624.0 | 592.5 | 967.9 | 866.9 | 838.4 | 1059.4 | 1010.7 | 979.6 | 845.5 | 679.1 | 792.4 | 672.5 |
| 22 | 524.7 | 281.3 | 831.5 | 767.5 | 843.3 | 1147.0 | 1317.6 | 1089.0 | 728.3 | 720.6 | 771.8 | 671.0 |
| 23 | 772.0 | 774.6 | 673.2 | 678.0 | 882.0 | 992.7 | 1146.7 | 1252.1 | 737.9 | 668.4 | 811.4 | 431.5 |

TABLE 10

| YEAR | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 24 | 458.6 | 497.1 | 636.9 | 934.5 | 863.9 | 714.4 | 648.5 | 754.3 | 615.3 | 688.2 | 737.3 | 680.7 |
| 25 | 621.2 | 925.8 | 773.5 | 1101.2 | 970.1 | 990.1 | 1163.6 | 1176.4 | 779.6 | 624.6 | 577.3 | 795.3 |
| 26 | 560.4 | 574.1 | 903.3 | 765.5 | 951.0 | 953.0 | 1120.7 | 1093.9 | 829.2 | 901.1 | 956.6 | 834.6 |
| 27 | 596.3 | 266.7 | 1132.4 | 998.8 | 889.1 | 639.6 | 557.7 | 717.2 | 531.5 | 597.2 | 737.3 | 588.4 |
| 28 | 730.6 | 752.5 | 772.0 | 1218.3 | 1107.8 | 713.2 | 748.6 | 890.6 | 647.7 | 626.9 | 848.2 | 1170.0 |
| 29 | 905.3 | 625.4 | 783.2 | 1016.9 | 1197.6 | 954.5 | 930.3 | 968.1 | 760.3 | 687.7 | 821.1 | 604.4 |
| 30 | 687.2 | 571.1 | 747.8 | 1001.0 | 1093.4 | 689.4 | 754.0 | 1063.8 | 674.7 | 716.4 | 728.4 | 769.4 |
| 31 | 865.3 | 807.1 | 914.8 | 912.3 | 838.6 | 570.4 | 669.4 | 745.0 | 696.4 | 676.3 | 721.6 | 770.8 |
| 32 | 534.6 | 703.1 | 772.0 | 1036.0 | 959.8 | 786.2 | 995.6 | 883.8 | 767.0 | 554.5 | 741.2 | 856.2 |
| 33 | 738.1 | 890.4 | 1188.5 | 962.7 | 816.5 | 877.2 | 1097.7 | 1150.9 | 800.6 | 654.3 | 546.4 | 575.5 |
| 34 | 499.1 | 425.2 | 926.8 | 938.7 | 822.8 | 1082.3 | 1035.6 | 940.3 | 757.7 | 726.5 | 945.2 | 612.9 |
| 35 | 872.5 | 777.9 | 952.3 | 780.3 | 949.5 | 669.5 | 894.9 | 914.2 | 724.2 | 882.5 | 970.2 | 673.4 |
| 36 | 682.4 | 528.9 | 584.4 | 972.1 | 1026.4 | 1133.4 | 1257.2 | 1158.4 | 801.1 | 774.4 | 788.0 | 717.8 |
| 37 | 497.7 | 431.6 | 761.5 | 768.2 | 1069.9 | 777.9 | 1015.3 | 1255.4 | 991.4 | 786.2 | 702.3 | 1208.8 |
| 38 | 901.0 | 842.2 | 1131.3 | 1140.9 | 1108.2 | 1058.1 | 1304.1 | 1022.0 | 707.0 | 635.7 | 930.1 | 913.3 |
| 39 | 757.7 | 677.1 | 974.5 | 1047.3 | 1006.9 | 1031.5 | 1211.3 | 1055.0 | 804.3 | 894.3 | 906.1 | 663.4 |
| 40 | 476.9 | 646.9 | 840.7 | 1175.7 | 1038.9 | 847.8 | 1183.2 | 968.4 | 760.2 | 630.6 | 703.5 | 767.4 |
| 41 | 744.3 | 717.7 | 598.0 | 715.4 | 761.6 | 944.1 | 1213.8 | 1101.5 | 525.6 | 610.0 | 622.7 | 595.7 |
| 42 | 605.8 | 953.2 | 693.9 | 873.5 | 972.1 | 1183.5 | 1087.4 | 1150.7 | 808.7 | 847.9 | 1061.9 | 1019.1 |
| 43 | 695.9 | 583.1 | 702.4 | 669.6 | 781.1 | 845.0 | 978.5 | 1070.0 | 870.3 | 762.7 | 878.4 | 1173.7 |
| 44 | 886.7 | 652.8 | 723.4 | 769.5 | 783.8 | 828.1 | 993.9 | 956.0 | 946.8 | 1012.8 | 1055.3 | 811.5 |
| 45 | 709.6 | 544.6 | 935.6 | 1094.2 | 989.9 | 1068.8 | 1272.6 | 1033.0 | 575.2 | 611.3 | 747.3 | 760.7 |
| 46 | 730.2 | 622.1 | 864.1 | 928.7 | 904.8 | 864.7 | 781.1 | 778.0 | 546.4 | 373.1 | 518.8 | 498.5 |
| 47 | 554.1 | 674.2 | 623.1 | 914.6 | 816.7 | 691.3 | 1092.3 | 1196.9 | 832.8 | 603.7 | 612.3 | 607.5 |
| 48 | 426.5 | 466.0 | 595.9 | 789.7 | 1028.4 | 654.9 | 1107.1 | 1297.9 | 773.8 | 796.3 | 934.8 | 863.7 |



TABLE 10

TABLE 10

| YEAR | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 49 | 949.3 | 418.9 | 942.0 | 914.2 | 705.8 | 1122.4 | 1088.1 | 872.5 | 538.8 | 561.9 | 903.4 | 972.6 |
| 50 | 735.6 | 528.8 | 853.8 | 1037.0 | 1060.9 | 675.6 | 770.2 | 883.4 | 1015.3 | 1064.4 | 1310.8 | 803.6 |
| 51 | 407.8 | 452.0 | 727.8 | 1039.7 | 935.6 | 709.3 | 873.1 | 991.0 | 545.2 | 496.4 | 523.6 | 1062.1 |
| 52 | 968.6 | 672.5 | 1022.5 | 1076.2 | 1018.2 | 746.5 | 975.5 | 828.3 | 670.9 | 612.2 | 756.6 | 684.3 |
| 53 | 769.9 | 845.2 | 834.3 | 1088.4 | 936.2 | 952.7 | 910.5 | 1195.8 | 953.4 | 872.0 | 1247.4 | 1019.7 |
| 54 | 1142.5 | 624.5 | 803.2 | 828.5 | 866.0 | 1273.8 | 1165.7 | 1378.2 | 781.0 | 911.2 | 930.3 | 1147.9 |
| 55 | 842.0 | 655.8 | 760.2 | 923.6 | 937.3 | 1230.0 | 1220.4 | 778.7 | 644.3 | 618.2 | 630.8 | 904.2 |
| 56 | 573.8 | 699.1 | 1069.7 | 928.5 | 874.7 | 1005.8 | 1084.9 | 774.4 | 567.7 | 606.1 | 853.8 | 816.4 |
| 57 | 741.0 | 540.7 | 991.1 | 972.1 | 1020.3 | 819.2 | 1112.8 | 1116.4 | 834.0 | 834.0 | 901.1 | 848.7 |
| 58 | 754.4 | 712.1 | 1021.6 | 933.8 | 848.1 | 1226.3 | 1263.7 | 1119.2 | 814.7 | 785.6 | 712.3 | 952.4 |
| 59 | 886.3 | 921.5 | 867.6 | 784.2 | 846.2 | 945.0 | 980.9 | 704.9 | 718.5 | 614.1 | 445.5 | 693.7 |
| 60 | 724.2 | 655.3 | 685.5 | 896.3 | 1104.1 | 939.8 | 1097.8 | 1177.9 | 902.7 | 828.6 | 883.6 | 1070.5 |
| 61 | 764.3 | 775.7 | 510.4 | 726.1 | 712.4 | 1269.7 | 1342.2 | 1258.0 | 968.5 | 792.1 | 621.2 | 1234.2 |
| 62 | 809.1 | 743.1 | 859.3 | 946.7 | 1022.8 | 916.0 | 1043.0 | 1161.8 | 670.0 | 581.4 | 802.8 | 675.3 |
| 63 | 570.8 | 733.0 | 834.3 | 993.4 | 940.0 | 815.2 | 984.3 | 799.6 | 701.3 | 739.3 | 988.5 | 1232.0 |
| 64 | 902.9 | 826.3 | 1051.7 | 998.7 | 997.3 | 665.5 | 877.4 | 1092.2 | 807.5 | 793.1 | 705.3 | 766.6 |
| 65 | 803.0 | 665.1 | 595.5 | 814.2 | 960.4 | 734.4 | 891.1 | 903.8 | 798.5 | 769.2 | 1030.1 | 907.5 |
| 66 | 948.2 | 1019.5 | 1251.6 | 1042.1 | 1018.9 | 971.1 | 866.7 | 804.0 | 595.4 | 451.7 | 545.8 | 669.4 |
| 67 | 850.0 | 526.3 | 755.4 | 1072.5 | 1042.8 | 818.7 | 976.0 | 813.5 | 706.0 | 442.5 | 448.4 | 598.4 |
| 68 | 895.5 | 550.6 | 1069.3 | 766.9 | 858.1 | 779.9 | 809.6 | 758.6 | 736.7 | 677.4 | 733.7 | 1028.2 |
| 69 | 1000.9 | 770.1 | 1047.2 | 782.7 | 801.2 | 945.5 | 1088.6 | 823.2 | 718.9 | 669.9 | 855.2 | 930.8 |
| 70 | 630.0 | 813.9 | 495.4 | 638.5 | 918.2 | 1015.9 | 1011.5 | 714.7 | 696.6 | 825.4 | 775.5 | 894.8 |
| 71 | 797.2 | 821.4 | 670.2 | 804.0 | 859.0 | 617.4 | 846.1 | 800.8 | 595.7 | 496.0 | 634.6 | 682.6 |
| 72 | 988.6 | 830.3 | 753.9 | 1234.4 | 1235.3 | 781.3 | 899.3 | 871.0 | 726.4 | 755.6 | 879.1 | 848.7 |
| 73 | 677.0 | 706.9 | 605.6 | 924.4 | 960.3 | 799.4 | 1039.5 | 1088.5 | 811.1 | 718.2 | 887.5 | 720.2 |

SHEET 3 OF 5 SHEETS

TABLE 10

| YEAR | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 74 | 720.5 | 643.1 | 1064.2 | 818.1 | 846.9 | 807.9 | 946.1 | 823.4 | 610.1 | 543.5 | 839.8 | 776.2 |
| 75 | 684.7 | 942.2 | 795.7 | 962.3 | 629.6 | 1193.7 | 1180.0 | 1347.3 | 763.7 | 783.1 | 853.2 | 619.1 |
| 76 | 472.3 | 946.9 | 798.6 | 1192.5 | 1062.9 | 960.4 | 1162.7 | 1102.5 | 971.8 | 827.3 | 773.8 | 810.5 |
| 77 | 638.9 | 656.4 | 833.2 | 931.6 | 1111.2 | 603.3 | 721.5 | 859.7 | 719.3 | 947.2 | 920.2 | 528.3 |
| 78 | 509.4 | 633.2 | 703.4 | 855.8 | 875.1 | 902.2 | 1191.9 | 1022.6 | 509.4 | 674.1 | 541.5 | 833.7 |
| 79 | 793.2 | 389.3 | 752.4 | 923.5 | 1114.5 | 1086.9 | 1191.4 | 1206.2 | 692.5 | 759.5 | 741.4 | 937.1 |
| 80 | 837.8 | 503.9 | 660.9 | 1077.0 | 1025.0 | 719.8 | 907.9 | 935.5 | 773.1 | 717.7 | 784.8 | 1035.7 |
| 81 | 839.0 | 690.4 | 672.7 | 928.7 | 794.0 | 649.6 | 661.2 | 567.3 | 688.3 | 731.4 | 863.2 | 1135.0 |
| 82 | 757.3 | 557.6 | 1138.9 | 1008.4 | 931.6 | 883.4 | 797.3 | 927.5 | 667.6 | 597.3 | 798.9 | 854.0 |
| 83 | 851.9 | 618.6 | 761.6 | 1028.5 | 1042.5 | 951.2 | 1100.3 | 1330.2 | 795.2 | 691.0 | 752.2 | 355.3 |
| 84 | 572.5 | 883.0 | 677.0 | 811.4 | 1000.3 | 1034.2 | 1250.8 | 1162.8 | 745.4 | 858.7 | 1125.9 | 902.4 |
| 85 | 825.6 | 716.7 | 859.8 | 866.2 | 1158.9 | 687.9 | 982.1 | 1071.8 | 699.3 | 570.6 | 737.1 | 961.6 |
| 86 | 746.4 | 647.9 | 889.6 | 933.6 | 885.7 | 817.1 | 1155.6 | 1118.1 | 685.3 | 604.8 | 800.4 | 1171.2 |
| 87 | 909.3 | 431.9 | 695.3 | 963.7 | 973.8 | 399.1 | 733.4 | 760.1 | 811.3 | 847.4 | 891.0 | 1039.4 |
| 88 | 971.5 | 307.1 | 1081.4 | 946.3 | 765.8 | 931.7 | 937.7 | 1028.7 | 731.5 | 725.2 | 615.8 | 587.8 |
| 89 | 663.1 | 273.1 | 633.4 | 795.5 | 850.9 | 845.5 | 1094.4 | 811.7 | 543.0 | 526.3 | 703.3 | 743.9 |
| 90 | 661.8 | 528.0 | 672.7 | 971.2 | 872.2 | 637.7 | 583.9 | 807.9 | 752.7 | 694.3 | 565.9 | 674.0 |
| 91 | 574.0 | 974.8 | 919.4 | 796.2 | 1040.1 | 777.2 | 723.7 | 672.4 | 481.5 | 376.9 | 597.6 | 1024.0 |
| 92 | 756.6 | 394.6 | 870.8 | 1047.7 | 967.5 | 906.4 | 859.8 | 846.5 | 768.1 | 762.6 | 809.8 | 799.2 |
| 93 | 542.8 | 495.9 | 801.2 | 995.1 | 940.5 | 658.5 | 834.7 | 771.5 | 634.6 | 554.8 | 559.8 | 757.4 |
| 94 | 652.0 | 839.1 | 690.4 | 658.0 | 936.1 | 800.2 | 757.9 | 691.9 | 594.3 | 656.2 | 686.6 | 1103.2 |
| 95 | 1163.8 | 1017.7 | 699.5 | 882.9 | 846.9 | 695.0 | 777.8 | 1052.4 | 628.6 | 515.9 | 554.0 | 349.7 |
| 96 | 667.3 | 592.5 | 1168.9 | 703.3 | 763.7 | 832.5 | 1189.6 | 1156.5 | 899.5 | 878.1 | 869.3 | 1051.0 |
| 97 | 1102.0 | 582.0 | 987.0 | 1077.6 | 1077.5 | 1020.8 | 1117.8 | 1152.5 | 882.1 | 986.7 | 990.5 | 622.7 |
| 98 | 377.2 | 498.3 | 901.2 | 774.4 | 779.1 | 775.4 | 1039.9 | 1220.5 | 955.8 | 757.8 | 1008.7 | 893.5 |

TABLE 10

| YEAR | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 99 | 803.2 | 664.4 | 593.9 | 994.4 | 981.2 | 864.0 | 1114.8 | 1042.9 | 886.2 | 615.3 | 921.5 | 1173.9 |
| 100 | 915.0 | 780.5 | 1007.2 | 959.8 | 939.8 | 800.6 | 853.1 | 1000.7 | 777.0 | 721.9 | 803.6 | 836.2 |

SHEET 5 OF 5 SHEETS

100 year low flow has not yet been experienced.

The chief reason for generating an expanded flow series is for the evaluation of length, severity and distribution of droughts. The Kohala Ditch system has practically no storage and agriculture depends on daily flows collected from streams draining to the system. Without storage, vagaries of weather in the Awini and Honokane drainage basins dictate agricultural practices in the irrigated region. If the frequency distribution, length and severity of droughts can be reasonably estimated, the long term economic feasibility of an agriculture depending on surface water as its chief supply for irrigation can be assessed.

Periods of low flow (droughts)

Dry weather in the drainage area of the ditch system causes below normal flows, the continuation of which for long periods of time implies drought conditions. The definition of a drought differs from one situation to another; in some cases prolonged dry periods may have minimal effects on agriculture while in others short periods of below normal rainfall may be disastrous. The irrigated portion of the Kohala agricultural region is detrimentally affected by relatively short dry periods unless groundwater is pumped to the ditch level.

For Kohala, a reasonable definition of a drought would include all periods in which three or more consecutive months experienced less than normal ditch flow. Drought intensity may be further categorized as severe, moderate and ordinary. A severe drought is defined as a run of 3 or more months of low flow during which at least one of the months has a flow about 50% or more below normal and the others have flows about 50% to 75% of normal. Because the coefficient of variation of the distribution of all flows is approximately .24, the above definition may be stated as:

$$q_i \leq \bar{q}_i - 2s;\ t \geq \text{ 1 month}$$

$$\bar{q}_j - 2s < q_j \leq \bar{q}_j - 1s;\ t \geq \text{ 2 months}$$

A moderate drought is defined as a run of 3 or more months when the flow lies between one and two standard deviations below normal, or:

$$\bar{q}_i - 2s < q_i \leq \bar{q}_i - 1s;\ t \geq \text{ 3 months}$$

Severe and moderate droughts as defined above are relatively infrequent. However, dry periods are common and their frequency of occurrence causes inconveniences for agriculture. These periods are classed as ordinary droughts and are arbitrarily defined as any series of 3 or more months which suffer lower than normal flows, stated as:

$$q_j < \bar{q}_i;\ t \geq 3 \text{ months}$$

As defined above, ordinary droughts include severe and moderate droughts as sub-sets.

In the evaluation which follows both the historical and lag-1 models are analyzed to establish the length, frequency and severity of droughts and their probabilities of occurrence. The models yield generally similar conclusions, although the lag-1 model somewhat underestimates the frequency of severe and moderate droughts. However, the total set of droughts as predicted by the lag-1 model closely corresponds to the experience of the historical record.

Severe and Moderate droughts

Table 11 lists the severe and moderate droughts implied by low flow periods extracted from the USGS record at 7510 between 1928 and 1965, and the same categories extracted from the 100 year lag-1 simulation. A set of 4 consecutive months (July through October) in 1930, when the historical record shows each month to have a flow $q < \bar{q} - 2s$, is not included because the probability of such an occurrence is extraordinarily slim; it is not clear why these months are so deficient in flow but the likeliest explanation involves maintenance problems. Excluding this sequence, in 37 years of record (extended to 1965 to include dry years early in the decade) 4 severe droughts totalling 14 months and 5 moderate droughts totalling 17 months were experienced. Historically, therefore, severe and moderate droughts accounted for 7% of the time, and one or the other could be expected to occur about once in four years. The lag-1 model predicts that severe and moderate droughts should account for 4.3% of the time and have an expectation occurrence of once in about six and a half years. The difference between the models suggests that the last 37 years has been slightly abnormal in experiencing bad droughts.

Table 11 also gives the expected lengths of severe and moderate droughts and the expected frequency of these lengths. The simulation and historical models are in relatively good agreement, both models stating that most of the severe and moderate droughts are of 3 to 4 months duration and that none is longer than 5 months.

Also included in table 11 is the expectation of drought occurrence for each month of the year. Both models confirm that moderate and severe droughts happen most frequently in the sequence of months from July through December, but that drought is likely to occur with nearly equal probability in any month of the year. At first glance this seems to be a rather surprising conclusion because the summer-fall months are the ones most noticed and remembered, but in summer and fall plant requirements are greatest and lack of water most harmful, while in the winter and spring months plant requirements are lower and not as much irrigation is required.

Ordinary droughts

Ordinary droughts as defined include moderate and severe droughts, which however account for only a small fraction of the total set of droughts. Table 12 gives the frequencies of ordinary droughts as extracted from the historical record and the lag-1 simulation model. Both models agree with each other in showing a high frequency of occurrence of droughts, with about 35% of all months falling in a sequence of 3 or more months of less than normal flow, and with the exceptation of drought in 3 out of 4 years. It is this high frequency of occurrence of 3 or more months of below normal flow which is responsible for the seemingly permanent claim that drought

Table 11

Severe and Moderate Droughts

Kohala Ditch System

Historical Record 1928 - 1965

1. Severe

1933: Sept.-Oct.-Nov.

1955: Jan. -Feb.-March

1955- 56: Nov. -Dec.-Jan.

1965: May -June - July - Aug. - Sept.

Total no. years occurrence --- 4

Total months drought ------ 14

2. Moderate

1934: Oct. - Nov. - Dec.

1935: July - Aug. - Sept.

1940: Mar. - Apr. - May

1943-44: Nov. - Dec. - Jan. - Feb. - Mar.

1961: July - Aug. - Sept.

Total no. years occurrence----5

Total months drought ------- 17

Lag - 1 Model

1. Severe

June-July-Aug.-Sept.

Dec.-Jan. - Feb. - Mar.

Oct. - Nov. - Dec.

Total no. years occurrence...3

Total months drought... 11

2. Moderate

Total No. years occurrence--12

Total months drought---- 40

Table 11 (continued)

3. Length of moderate and severe droughts

| | Consecutive months | | | | | |
|---|---|---|---|---|---|---|
| | 3 | % of Total | 4 | % of Total | 5 | % of Total |
| Historical | 7 | 78 | | | 2 | 22 |
| Lag-1 | 9 | 60 | 6 | 40 | | |

4. Frequency of moderate and severe droughts by months

| | Jan. | Feb. | Mar. | Apr. | May | June |
|---|---|---|---|---|---|---|
| Historical Frequency: % | 9.7 | 6.5 | 9.7 | 3.2 | 6.5 | 3.2 |
| Lag-1 Frequency: % | 5.9 | 5.9 | 9.8 | 5.9 | 5.9 | 5.9 |

| | July | Aug. | Sept. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|
| Historical Frequency: % | 9.7 | 9.7 | 12.9 | 6.5 | 12.9 | 9.7 |
| Lag-1 Frequency: % | 9.8 | 9.8 | 11.8 | 9.8 | 9.8 | 9.8 |

is in progress or has just been experienced.

The statistics of length of ordinary droughts are summarized in table 12. Most common droughts are restricted to 3 or 4 months (the median in both models is 4 months), yet historically one ordinary drought went on for 14 months and in the lag-1 model a drought of 11 months was generated. About 75% of all droughts have lengths of 6 months or less.

Table 12 also gives the probability of drought occurrence for each month. As in the case of severe and moderate droughts, the frequency of ordinary droughts is not greatly different among the months. April is the month of lowest expectation in both models, while June has the highest expectancy by the historical period and December by the lag-1 simulation, though June also has a high expectancy in the lag-1 model and December in the historical model. The summer and fall months in each model have a better than 1 out of 3 chance of suffering drought.

Comments On Droughts

Ordinary droughts, defined as a consecutive run of 3 or more months of sub-normal flow, are relatively common, include about 35% of all months on a long term basis, and can be expected approximately once every 1.5 years, but moderate and severe droughts are infrequent, accounting for only about 5% of the total months and having an expectancy of about one in five years. An ordinary drought can persist for as long as a year, although most are 3 to 4 months in

Table 12

Ordinary Droughts

Kohala Ditch System

1. Frequency

| | No. Years | % Years | No. Mos. | % Total Months |
|---|---|---|---|---|
| Historical (1928-60) | 25 | 75.6 | 136 | 34.8 |
| Lag-1 (100 years) | 76 | 76.0 | 428 | 35.7 |

2. Length and frequency of length

| | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Historical** | | | | | | | | | | | | |
| No. series | 7 | 7 | 4 | 3 | | 2 | 1 | 1 | | | | 1 |
| % total mos. | 5.4 | 7.2 | 5.1 | 4.6 | | 4.1 | 2.3 | 2.6 | | | | 3.6 |
| **Lag-1** | | | | | | | | | | | | |
| No. series | 32 | 21 | 13 | 9 | 8 | 3 | 2 | 2 | 1 | | | |
| % total mos. | 8.0 | 7.0 | 5.4 | 4.5 | 4.7 | 2.0 | 1.5 | 1.7 | 0.9 | | | |

3. Drought frequency by months

| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Historical | 36.4 | 30.3 | 27.3 | 24.2 | 33.3 | 42.4 | 41.9 | 41.9 | 31.3 | 36.4 | 36.4 | 36.4 |
| Lag-1 | 41.0 | 36.0 | 30.0 | 25.0 | 30.0 | 36.0 | 36.0 | 39.0 | 38.0 | 36.0 | 36.0 | 44.0 |

length, while moderate and severe droughts last no longer than 5 months and average 3 months in length.

The statistics show that probability of drought is not greatly different among the months of the year, though moderate and severe droughts are slightly more frequent in late summer and fall. Winter droughts are not as noticeable as the summer-fall droughts because irrigation demand is lower then. Below-normal flows in the months of September and October are especially hard on agriculture because normal flows for these months are among the lowest for the year.

Although most droughts are mild, irrigated agriculture would suffer serious setbacks unless supplemental groundwater were available because the ditch system has very little surface storage. The surplus flows of the ditch are not saved for use during dry periods and at best are used to recharge the groundwater aquifer. Fortunately ditch flow is not absolutely a function of meteorological probabilities; high-level water from Honokane Nui yields an assured minimum ditch flow of nearly 10 mgd whether or not it rains. Without this input, periods of zero and very low ditch flow would be common and it is not likely that irrigated agriculture could have been or could be successful.

The Markov lag-1 simulation model reflects the historical record within reasonably close limits, especially with regard to duration and frequency of ordinary droughts. The lag-1 model, however, is not meant to be a replication of the historical record but is devised to create a long flow series from which the probabilistic characteristics of the series could be extracted on the assumption that the historical record would not be long enough to give meaningful extreme characteristics. The simulation model indicates, however, that within the 33 year historical record the worst 100 year drought has already been experienced.

<u>Awini and Honokane Sectors of the Kohala Ditch System</u>

The Phase II report described and discussed the environmental setting and characteristics of flow of the Awini and Honokane Nui sectors of the Kohala Ditch System, which account for practically all of the flow at Gage 7510, and concluded that the collection efficiency of these sectors, though quite good, could be enhanced to some extent. Of the measured average flow of 27 mgd at Gage 7510, between 24 and 25 mgd are derived from the Awini and Honokane Nui sectors and the remainder from East and West Honokane Iki (1 to 2 mgd) and West Honokane Nui and Pololu (about 1 mgd).

The Awini sector, whose flow had been measured at Gage 7430, extends from East Honokane Iki eastward to the right branch, which is the main stem, of Waikaloa Stream and collects water from 16 streams, the largest of which, Ohiahuea, has a drainage area of 1.55 sq. miles and the smallest a drainage area of .03 sq. mi. The long term average flow measured at 7430 was 11.7 mgd, but the total average natural runoff of the 16 streams at the tunnel elevation is estimated at 45 mgd. The measured flow seems small in comparison with the natural runoff, but the inability of the system to collect all of the water is a result of the high instantaneous flow rates of the streams which can be accommodated by neither the intake nor transmission structures. The transmission tunnel is absolutely limiting; its apparent maximum flow capacity is approximately 35 mgd. Nevertheless, the evaluation in the Phase II Report indicated that an additional average of about 5 mgd could be handled by the system if improvements, especially to the intakes and flumes, were made. Refinement of the initial analyses suggest this amount is the upper limit. In other words, more than half the natural Awini drainage could never be collected by the present system.

The Awini sector has a map length of nine miles and is traversed by 25 miles of mule trails which require constant and careful maintenance. It is relevant, therefore, to ask how much net inflow would be lost to Gage 7510 if a part or all of Awini were abandoned. All of the low flows, when water is most desperately needed by agriculture, would be lost, but at higher flows some of the excess direct surface runoff from East Honokane Nui would make up for Awini losses, so that the total average loss to Gage 7510 would not equal the average flow at Gage 7430. Whether profitable agriculture in the Kohala region could survive without Awini sector flows can only be answered by an economic feasibility study.

Unlike the Awini sector, Honokane Nui is a relatively simple system. The stream combines with Awini flow just above a small dam on the west side of which the Kohala Ditch intake is situated. The dam is at present filled with alluvium and a portion of the stream water, which otherwise would drain to the intake, escapes over the parapet. The East Honokane Nui base flow, the spillage from high level dike compartments, amounts to 9 - 10 mgd, about 37% of the average flow at Gage 7510. This base flow is fixed and probably never goes below 9 mgd. An additional component of approximately 3 mgd of direct runoff from the stream reaches the intake, which means that 48% of the average at 7510 is East Honokane Nui water. There is no question that East Honokane Nui is the heart of the Kohala Ditch System; without its reliable base flow no agriculture is possible. It is fortunate that this sector is in the mid-portion of the collection and transmission system and that its upkeep is relatively uncomplicated. Its base flow alone justifies its retention for whatever uses are made of the Kohala lands.

East Honokane Nui Canyon also holds promise for the development of high level water stored between dikes. No perment new sources are underdeveloped, unless the Kehena Ditch flows are diverted to the canyon, but stored water could be exploited by horizontal drilling and its withdrawal programmed.

In order to help planners in their decisions regarding the surface water resources collected by the Ditch System, analyses follow which deal with:

1. Enhancement of flows from the Awini sector
2. Enhancement of flows from East Honokane Nui
3. Evaluation of the combined Awini - East Honokane Nui flows to the Ditch
4. Net losses to the system by abandonment of all or portions of Awini

Evaluation of the flow characteristics of the Awini Sector

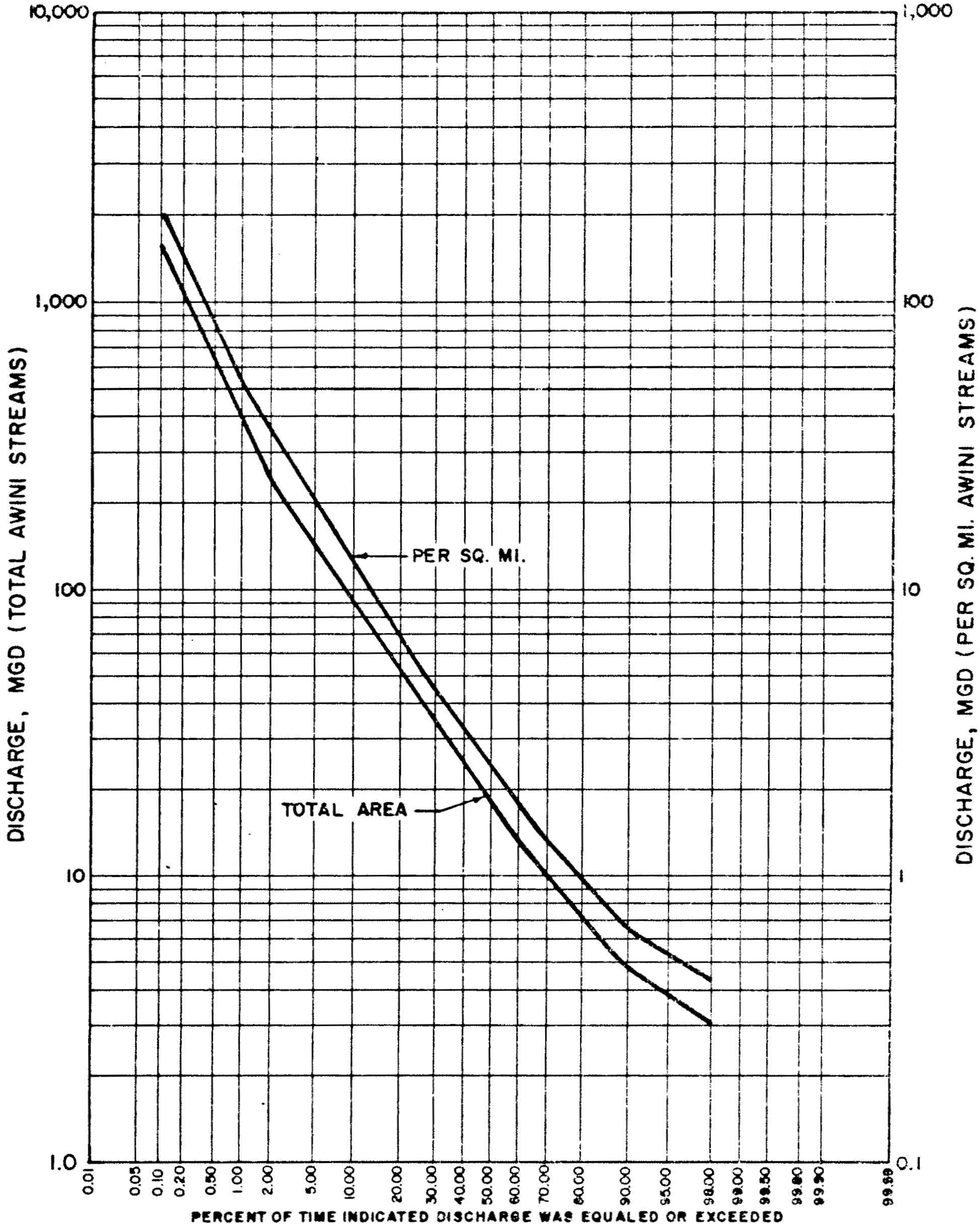
To exhibit the characteristics of flow at the elevation of the transmission tunnel, the Awini sector is treated as a single entity in which all elements of the system are working at their design level. The intakes are assumed to be able to accept all flow from the streams at all times so that the constraints on flow volume lie only with the transmission structures.

Recorded daily flow rates from 5 streams (Kukui, Paopao, Punalulu, Waiaalala, and Kaimu) to the east of the Awini sector are utilized by direct linear correlation to yield probabilistic and average natural flow values for the Awini streams. The correlation is considered reasonable because the drainage basins of both stream regions have similar geology, geomorphology, vegetative cover, and rainfall amount and distribution. Obviously the correlation cannot be exact, but it provides the only opportunity to evaluate in a quantitative manner the characteristics of the Awini streams.

The duration curve of natural flow, derived by the correlation discussed above, for the Awini sector as a whole and on a unit square mile basis is given in figure 1. In figure 2 the relationship between flow and the percentage of total flow volume over time contributed by all flows equal to or less than a given flow is plotted on both a regional and a unit square mile basis. By employing the flow duration and volume duration curves, the flow characteristics of a diversion system of limited capacity can be calculated.

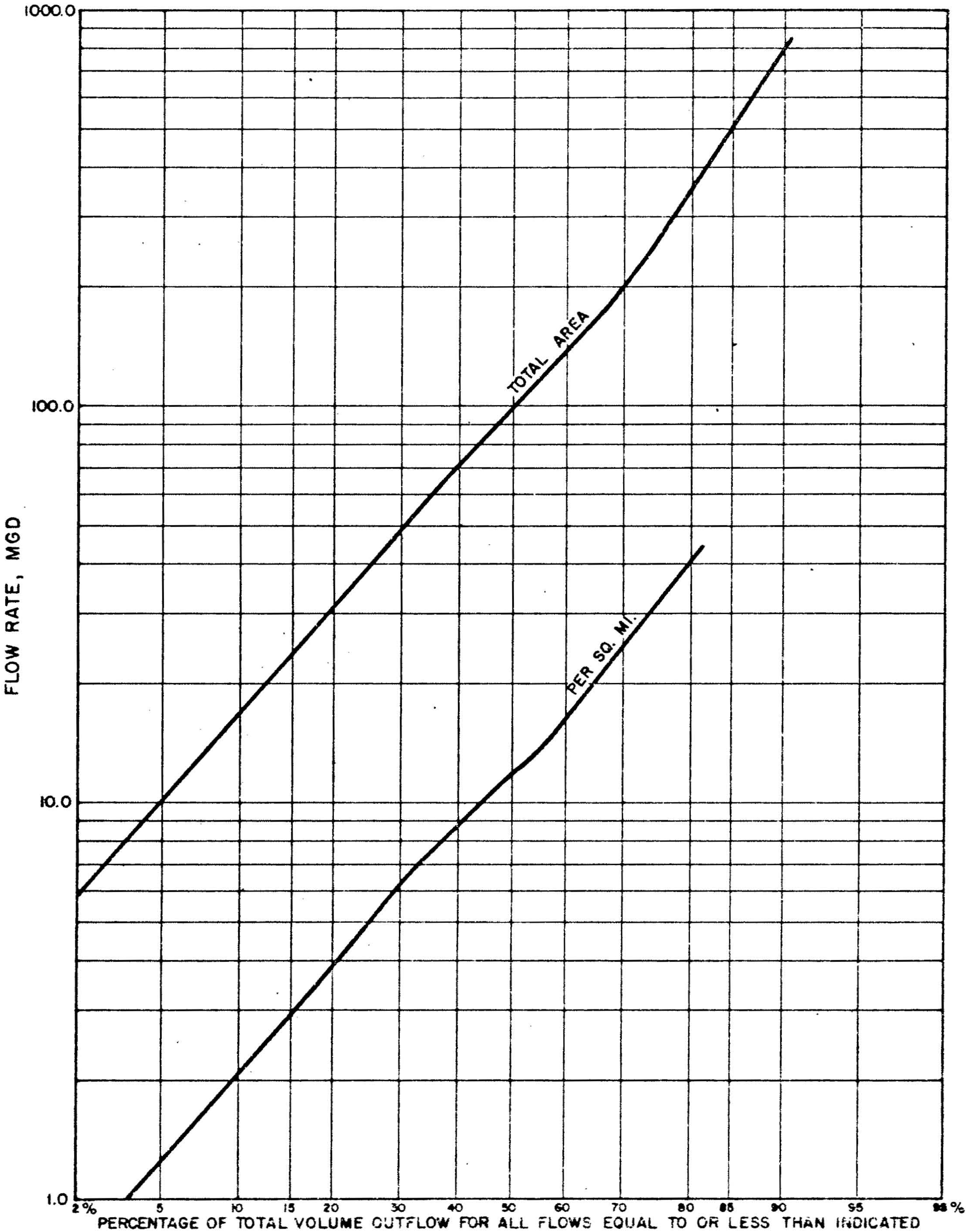
The standard method of reporting stream flow measurements is in the form of the average daily volume of water passing a stream section. This daily volume is the integral of all flow types -- ascending, maximum, descending, base and minimum flows. It is a single value which gives no information on the variety of flows which may occur during the day. This deficiency is particularly relevant in the analysis of a diversion system in which the capacity constraint may be exceeded or not reached by numerous flows during a single day. Without a continuous record of instantaneous flows the theoretical characteristics of a diversion system can only be estimated. The use of daily flows in the derivation of the yields of the Awini sector gives a first approximation of expectable flows, skewed somewhat to a higher than attainable level because the volume of instantaneous flows which are greater than the diversion capacity of the system are not accounted for in the computations where the daily flow value totals less than the diversion capacity. However, the transmission constraint on the Awini system (approx. 35 mgd)

FIGURE 1




AWINI SECTOR: FLOW DURATION CURVE NATURAL FLOW

FIGURE 2




AWINI SECTOR: NATURAL FLOW VOLUME DURATION CURVE is such that the approximations derived from daily flows are not unreasonable. These approximations should be considered the upper limits of hypothetical flows which would pass Gage 7430 if the system were constrained only by the size of the transmission works. An initial analysis using daily flows was given in the Phase II Report; more refined analyses follow.

Figure 2 (volume duration curve) gives the fraction, a, of the total Awini flow which is accounted for by all flows, $Q_i$, less than a given flow, $Q_p$. The average flow, $\bar{Q}_{i<p}$, for all flows less than $Q_p$ is given by:

(1) $\bar{Q}_{i<p} = \frac{a\bar{Q}}{t_{i<p}}$

in which $\bar{Q}$ is the recorded average daily flow of the stream and $t_{i<p}$ is the fraction of time in which the $Q_i$ are less than $Q_p$. Similarly, the average flow, $\bar{Q}_{i>p}$, for all flows greater than $Q_p$ is:

(2) $\bar{Q}_{i>p} = \frac{(1-a)\bar{Q}}{t_{i>p}}$

in which $t_{i>p}$ is the fraction of time in which the $Q_i$ are greater than $Q_p$. If the stream flows are collected by a diversion system of limiting capacity, $Q_c$, then for $Q_i < Q_c$ the average flow is the same as in (1) above with a being the fraction of the total volume outflow yielded by $Q_i < Q_c$ and $t_{i<c}$ the fraction of time in which these flows occur:

(3) $\bar{Q}_{i<c} = \frac{a\bar{Q}}{t_{i<c}}$

The average flow for those days when the $Q_i$ exceed $Q_c$ is equal to $Q_c$:

(4) $\bar{Q}_{i>c} = Q_c$

Therefore, the average flow of the constrained diversion system, $\bar{Q}_c$, over a period of time is:

(5) $\bar{Q}_c = t_{i<c} \; \bar{Q}_{i<c} + t_{i>c} \, Q_c$

or:

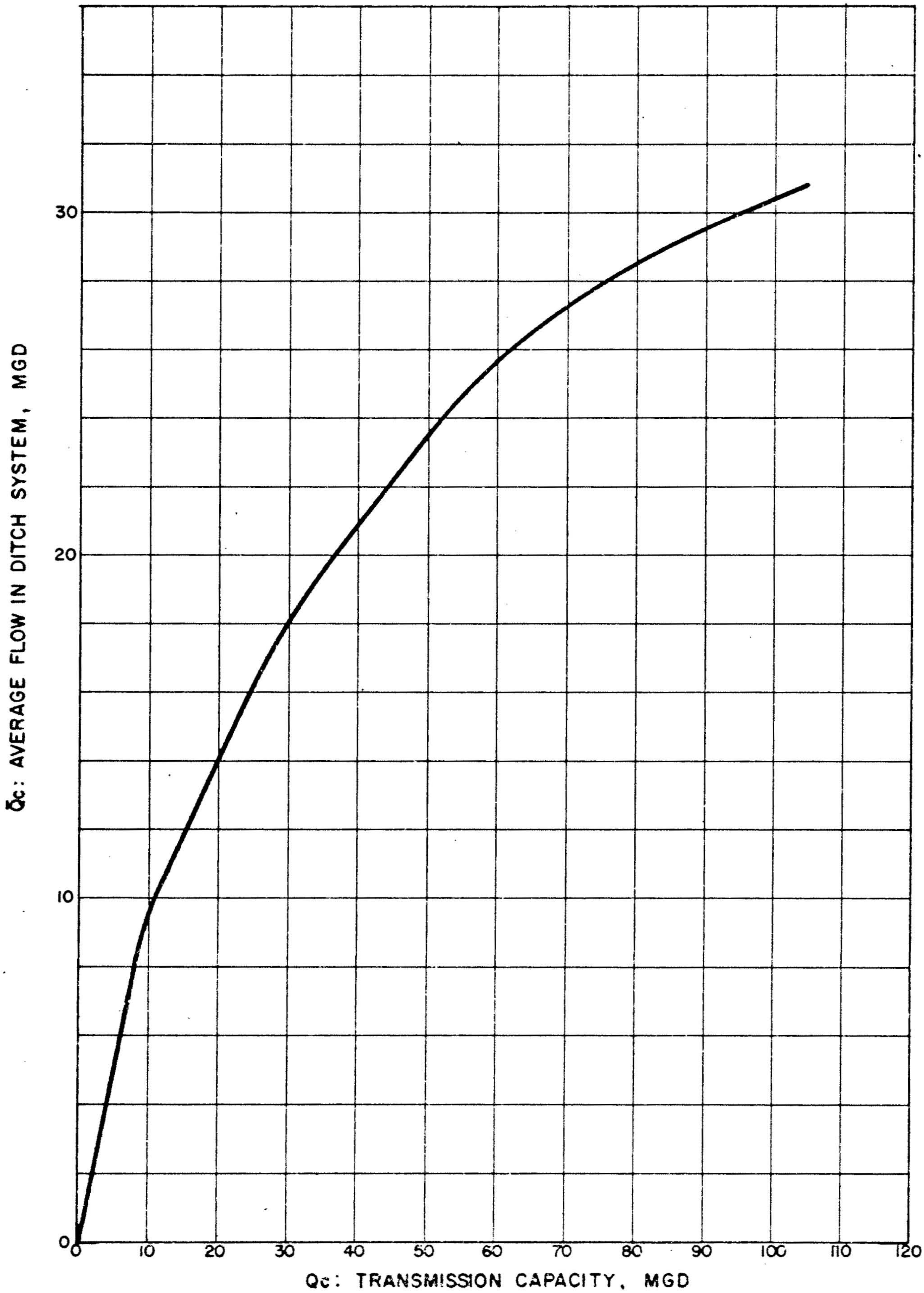
(6) $\bar{Q}_c = a \, \bar{Q} + t_{i>c} \, Q_c$

For example, $\bar{Q}_c$, the natural average daily flow of the Awini streams, is 45 mgd, and if the transmission capacity, $Q_c$, of the system is 35 mgd, from which it follows that a= .22 and $t_{i>c}$ = .28, then: $\bar{Q}_c = (.22)(45) + (.28)(35) = 19.7$ mgd

(in the Phase II Report, $\bar{Q}_c$ = 20.5 mgd).

The recorded average flow at Gage 7430 is 11.7 mgd, which is 59.4% of the theoretically possible average flow based on the daily flow model. The $\bar{Q}_c$ computed above is the upper limit of theoretical average flows; a more exact model would have to take into consideration instantaneous flow rates which escape being subsumed in the foregoing analysis, and the theoretical average flow would therefore be smaller than 19.7 mgd.

Equation (6) may also be used to evaluate the relationship between diversion capacity and the average flow of the contrained system. Figure 3 is a graph of average constrained flow, $\bar{Q}_c$, as a function of diversion capacity, $Q_c$. It is clearly evident that the rate of increase in average flow decreases as the diversion capacity becomes larger, which means that at some point the marginal value of the water would no longer justify the marginal cost of enlarging the system. For instance, doubling the transmission capacity from 35 mgd to 70 mgd would increase average yield by only




AWINI SECTOR: AVERAGE DAILY DITCH FLOW
AS FUNCTION OF TRANSMISSION CAPACITY
(THEORETICAL MODEL BASED ON AVERAGE DAILY FLOW)

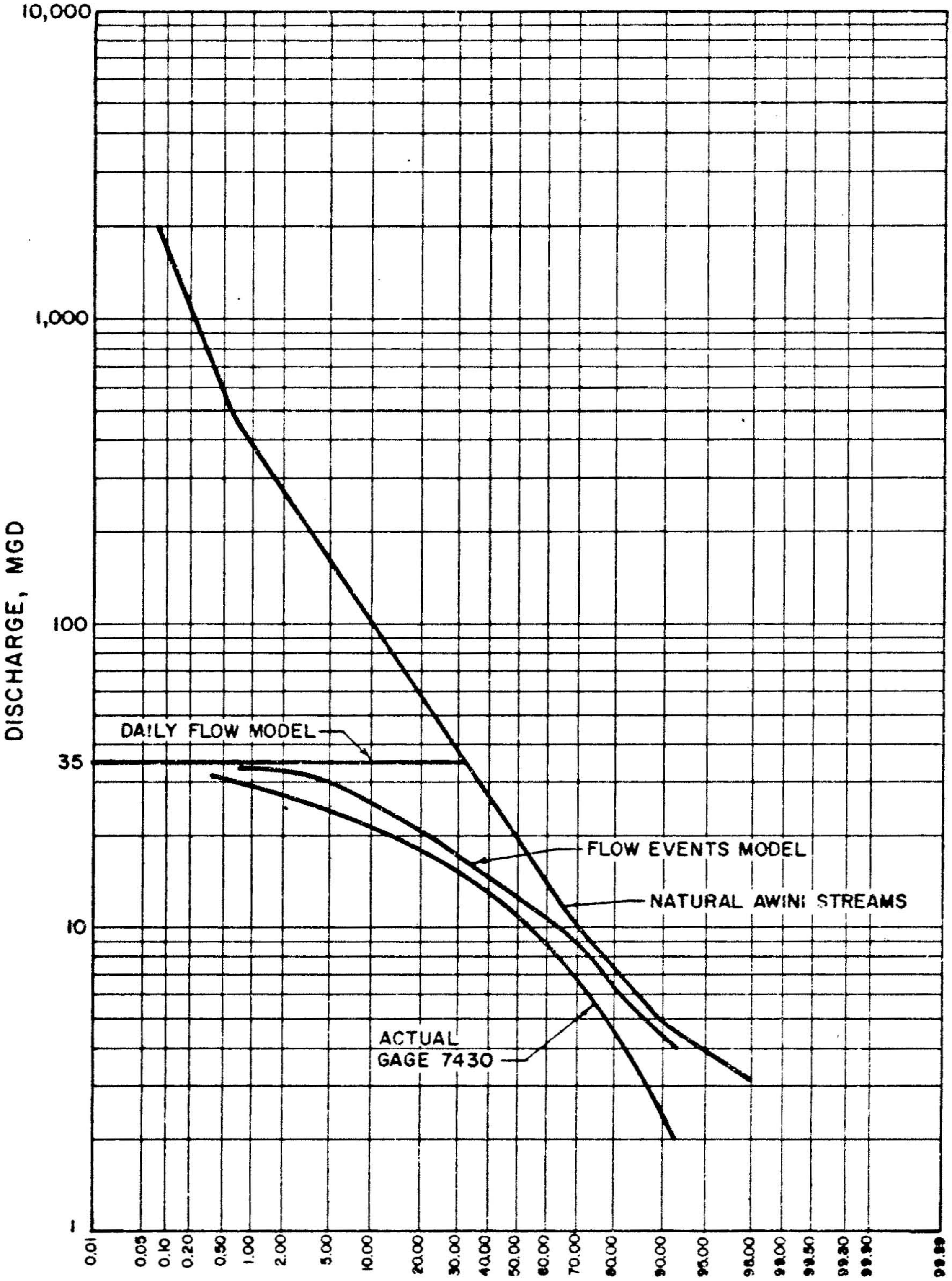
7.5 mgd. The system is surprisingly optimal as it exists in view of the paucity of data available at the time it was built early in the century.

<u>An Instantaneous Flow Events Model for the Awini Sector</u>

The model using daily average flows as the flow unit does not account for individual peak flows in the time continuum of each day but rather lumps all individual flow into the single daily flow volume. This lumped parameter may be too insensitive to yield accurate information on the theoretically divertable flow by a system with a given transmission constraint. In using the average daily flow rate the theoretically divertable flow as determined from equation (6) is overstated. In figure 4 the theoretical flow duration curve for the Awini system computed by equation (6) represents the upper limit of divertable flow through a transmission system with a capacity constraint of 35 mgd.

The instantaneous flow events model is an attempt to derive theoretically divertable flows from an evaluation of flow peaks and their decays in the time continuun. Unfortunately no continuous records of flows for the formerly gaged streams to the east of Awini are available in Hawaii, but to simulate the Awini sector streams continuous flow charts for USGS Gage 16-2000, which measures flow in the North Fork of Kaukonahua Stream on Oahu, have been used. This stream basin has many similarities to the Awini basins; both drain a high rainfall mountainous basalt terrane still in its natural state. Gage 2000 drains an area of 1.3 sq. mi. and shows a long term average flow of 10.8 mgd, equivalent to 7.8 mgd/sq. mi. The Awini unit drainage is 6.0 mgd/sq.mi.

FIGURE 4




AWINI SECTOR: FLOW - DURATION CURVES

Daily flow traces of Gage 2000 for the water year 1973-74 were examined and all events showing a rising and falling limb were noted. A total of 199 flow events were identified with peaks, $Q_I$, ranging from a maximum of 3500 cfs (2262 mgd) to a minimum of 5 cfs (3.2 mgd). The highest lumped daily average flow was 723 (467 mgd). The median of the flow events peak was 59 (38.1 mgd). The distribution of the peaks is very nearly log normal, as shown in figure 5 (a continuous straight line would represent a perfect log normal distribution).

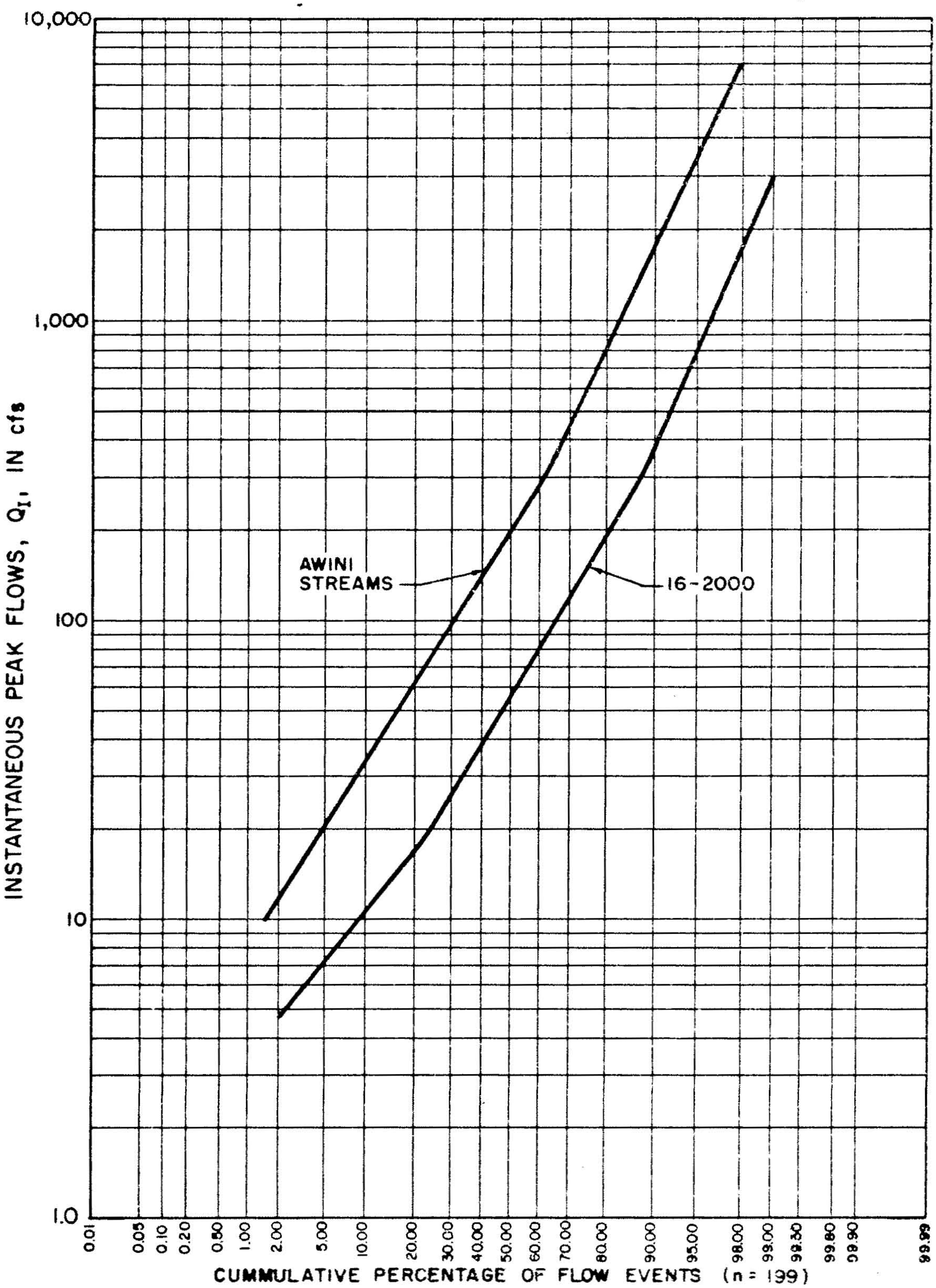
To convert the Gage 2000 flow events data to a log normal distribution for the Awini streams a direct linear correlation using the average unit flows for each basin was employed. During the 1973-74 water year the average flow at Gage 2000 was 12.3 mgd, equal to 8.9 mgd/sq. mi. Because the long term Awini average unit flow is given as 6 mgd/sq. mi. and the Awini drainage area is 7.5 sq. mi., the Gage 2000 data is transformed to Awini data as follows:

(7) $Q_I$ (Awini) = $3.64 Q_I$ (Gage 2000)

Figure 5 includes a plot of the distribution of flow event peaks of the Awini streams as determined from equation (7).

The structure of each flow event shows a rapid, nearly instantaneous climb to a peak flow, then a moderately steep decay. Flow volume for any event or class of events can be computed by determining the area under the ascending limb and the area under the descending limb until a new event starts with another ascending limb, and adding them. However, ascending limbs are invariably nearly vertical so that

FIGURE 5




FREQUENCY DISTRIBUTION OF PEAK FLOW EVENTS FROM DATA FOR NORTH FORK KAUKONAHUA STREAM, OAHU USGS GAGE 16-2000, WATER YEAR 1973-1974

AWINI CURVE DERIVED BY DIRECT LINEAR CORRELATION WITH 16-2000 the volumes are very much smaller than those determined for descending limbs, and therefore to make the analyses tractable, ascending limb volumes are ignored.

The flow rate on the decay limb of each event may be expressed as follows:

(8) $Q = Q_I \exp(-b t)$

in which $Q$ is flow rate at any time, $t$, after the start of decay from peak flow rate, $Q_I$, and $b$ is the decay constant. An analysis of 16 decay limbs over a range of flows for Gage 2000 gave values of the decay constant, $b$, ranging from 2.67 to 4.41, with a mean value of 3.37, which is used in further calculations. If the 199 events are assumed to be uniformly spaced in the time continuum, each event decays over 1.83 days from peak flow to the next peak flow. Again, to make the problem tractable, it is assumed the 199 events are uniformly spaced.

From equation (8) and the flow model described above, outflow volumes of the diversion system can be computed. The volume of flow, $V_t$, from $t = 0$ to $t = t$ is:

(9) $V_t = \frac{Q_I}{b} (1 - \exp(-b t))$

and the volume of flow, $V_{t_c}$, from $t = 0$ to $t = c$, is:

(10) $V_{t_c} = \frac{Q_I}{b} (1 - \exp(-b t_c))$

Therefore, the divertable volume of flow, $V_c$, is:

(11) $V_c = V_t - V_{t_c} + Q_c t_c$

and

(12) $V_c = \frac{1}{b} \left[ Q_c \left( \ln \frac{Q_I}{Q_c} + 1 \right) - Q_I \exp(-b t) \right]$.

The above holds true only for the following conditions:

$$Q_I > Q_c$$
$$0 < t_c < t.$$

If $Q_I < Q_c$, then:

(13) $V_c = \frac{Q_I}{b} \left(1 - \exp(-bt)\right)$

and if $t_c > t$ :

(14) $V_c = Q_c$

The theoretically obtainable flow for each frequency class (percentile range) can be computed by taking the $Q_I$ as given in figure 5 and applying (12), (13), or (14). The sum of the diversions for each class when divided by 365 yields the average theoretically possible diversion flow. Table 13 summarizes the relevant data and calculations for the Awini system for which a transmission capacity constraint of 35 mgd is assumed.

Table 13

Flow events model, Awini System. Transmission Capacity 35 mgd. (flow values in mg or mgd)

| Percentile Range | Inst. Flow $Q_r$ | Diverted volume $V_c$ | No. events $n$ | $nV_c$ | Daily Flow $V_c/1.83$ |
|---|---|---|---|---|---|
| 100-95 | 12 | 3.6 | 10 | 36 | 1.97 |
| 95-90 | 19 | 5.6 | 10 | 56 | 3.06 |
| 90-80 | 35 | 10.4 | 20 | 208 | 5.68 |
| 80-70 | 52 | 14.5 | 20 | 290 | 7.92 |
| 70-60 | 82 | 19.2 | 20 | 384 | 10.5 |
| 60-50 | 118 | 22.9 | 20 | 458 | 12.5 |
| 50-40 | 165 | 26.4 | 20 | 528 | 14.4 |
| 40-30 | 235 | 30.0 | 20 | 600 | 16.4 |
| 30-20 | 353 | 34.2 | 20 | 684 | 18.7 |
| 20-10 | 635 | 40.1 | 20 | 802 | 21.9 |
| 10- 5 | 1412 | 47.9 | 10 | 479 | 26.2 |
| 5- 2 | 3529 | 56.1 | 6 | 337 | 30.7 |
| 2- 1 | 5882 | 59.9 | 2 | 120 | 32.8 |
| 1- 0 | 8235 | 62.0 | 2 | 124 | 33.9 |
| | | | Total | 5106 | |

Av. 5106/365=14.0 mgd

In the above the computed theoretical average diverted flow is 14 mgd, which compares with the actual average flow at Gage 7430 of 11.7 mgd. The instantaneous events model thus gives a value within 2.5 mgd of the actual while the model employing lumped daily flows gives a theoretical average 8 mgd greater than the actual.

The average value of 14 mgd is the lower limit of the theoretically divertable flow of the Awini sector and the daily flow model average of 19.7 mgd is the high limit. It is manifest that the flashy nature of the streams, coupled with the limited transmission capacity, restricts the system to a potential average yield of between 14 and 20 mgd, probably closer to 14 than to 20. The synthetic flow duration curve for the instantaneous events model is plotted in figure 4 and shows that at flows below the median the potential increase over actual flows is about 3 mgd. Thus at the 70 percentile, actual diverted flow is 7 mgd, but potentially it should be between 9 and 10 mgd. This is not a great increase although it would occur when water was most needed.

The components of the Awini system are easily disrupted by high turbulent flows which carry bed load and trash to the intakes and into the transmission tunnels. Trash and bed load quickly clog the intakes, especially where the collection pools are filled with sediment, as most are now. Without regular maintenance, neither the flows recorded during the period of stable plantation activity nor the theoretical potentials derived above could be maintained.

Evaluation of flows from the East Honokane Nui Sector

In the Phase II report low flows of the Awini sector at Gage 7430 were correlated with low flows at Gage 7510 to provide equations from which the groundwater flow and the direct surface runoff of East Honokane Nui could be determined. From the low flow data, an extrapolation to the average direct surface runoff of East Honokane Nui was made, but flow from West Honokane Nui was neglected because it was assumed that no intake was connected with the tunnel from the stream. However, during subsequent field work the ditchmen stated that water cascades into the tunnel at the base of a waterfall on the stream. The average direct surface runoff of 13.8 mgd for East Honokane Nui computed in Phase II is therefore wrong by 5.2 mgd, which is assignable to West Honokane Iki; the corrected value is 8.6 mgd.

The correlation equation and its extension to average natural flows is as follows (values in mgd):

(1) $Q_{7510} = 9.7 + 1.5 Q_{7430}$

In which $Q_{7510}$ is flow at Gage 7510, $Q_{7430}$ is flow at Gage 7430, and 9.7 is base flow of East Honokane Nui Stream. Letting $Q_t$ be the sum of the average natural flows of West Honokane Iki (5.2 mgd), East Honokane Iki (4.2 mgd), West Honokane Nui (4.0 mgd) and Pololu (0.5 mgd), then equation (1) can be reformulated as average natural flows in the following way:

(2) $\bar{Q}_{7510} = 9.7 + \bar{S} + Q_{7430} + \bar{Q}_i$

in which $\bar{S}$ is the average natural direct surface runoff of East Honokane Nui, to give:

(3) $\bar{S} + \bar{Q}_i = 0.5\ \bar{Q}_{7430} = 22.5$ mgd

because the average natural flow of the Awini sector is 45 mgd.

Thus:

(4) $\bar{S} = 22.5 - 13.9 = 8.6$ mgd

which is the average natural direct surface runoff of East Honokane Nui and does not include either the base groundwater flow or the drainage which is pirated by the Kehena Ditch at the southern limit of the Honokane Nui drainage basin. If the Kehena Ditch were not intercepting Honokane Nui's water, the total average natural surface runoff would be (8.6 mgd + 7.4 mgd) = 16.0 mgd.

The total average flow of East Honokane Nui reaching the dam of the Kohala Ditch intake is:

(5) $\bar{Q} = 9.7 + 8.6 = 18.3$ mgd

but not all of the flow enters the ditch because of losses due to overflow at the dam during high instantaneous stream flows. From East and West Honokane Iki, West Honokane Nui and Pololu the actual average input to the ditch totals about 2.5 mgd, which when added to Gage 7430 gives (11.7 + 2.5) = 14.2 mgd. Since the average flow at Gage 7510 is 27 mgd, the average contribution from East Honokane Nui is (27-14.2)= 12.8 mgd. Of this contribution, 9.7 mgd is base flow groundwater, leaving an average direct surface runoff of 3.1 mgd, which is 5.5 mgd less than the average total direct surface runoff.

A portion of this 5.5 mgd which spills over the dam would go to the intake if the Awini system were blocked off, but much of it would nevertheless be lost during high stream stages. In an attempt to determine the proportion of the 5.5 mgd which would replace lost Awini water, computer simulations were run using the instantaneous flow events model described in the section dealing with the Awini system and a Kohala Ditch tunnel capacity of 70 mgd. The model giving the best fit to the average natural flow of East Honokane Nui (Model $\bar{Q}$= 18.1; eq.(5) $\bar{Q}$= 18.3 mgd) yielded a tunnel input of 13.9 mgd, a gain of 1.1 mgd mgd over the computed actual contribution of 12.8 mgd when Awini also flows to the intake. The synthetic flow duration curve for the simulation model, adjusted to include West Honokane Nui but ignoring Pololu stream because its contribution is small, is given in figure 8.

Consequences of losing all or portions of the Awini Sector flows

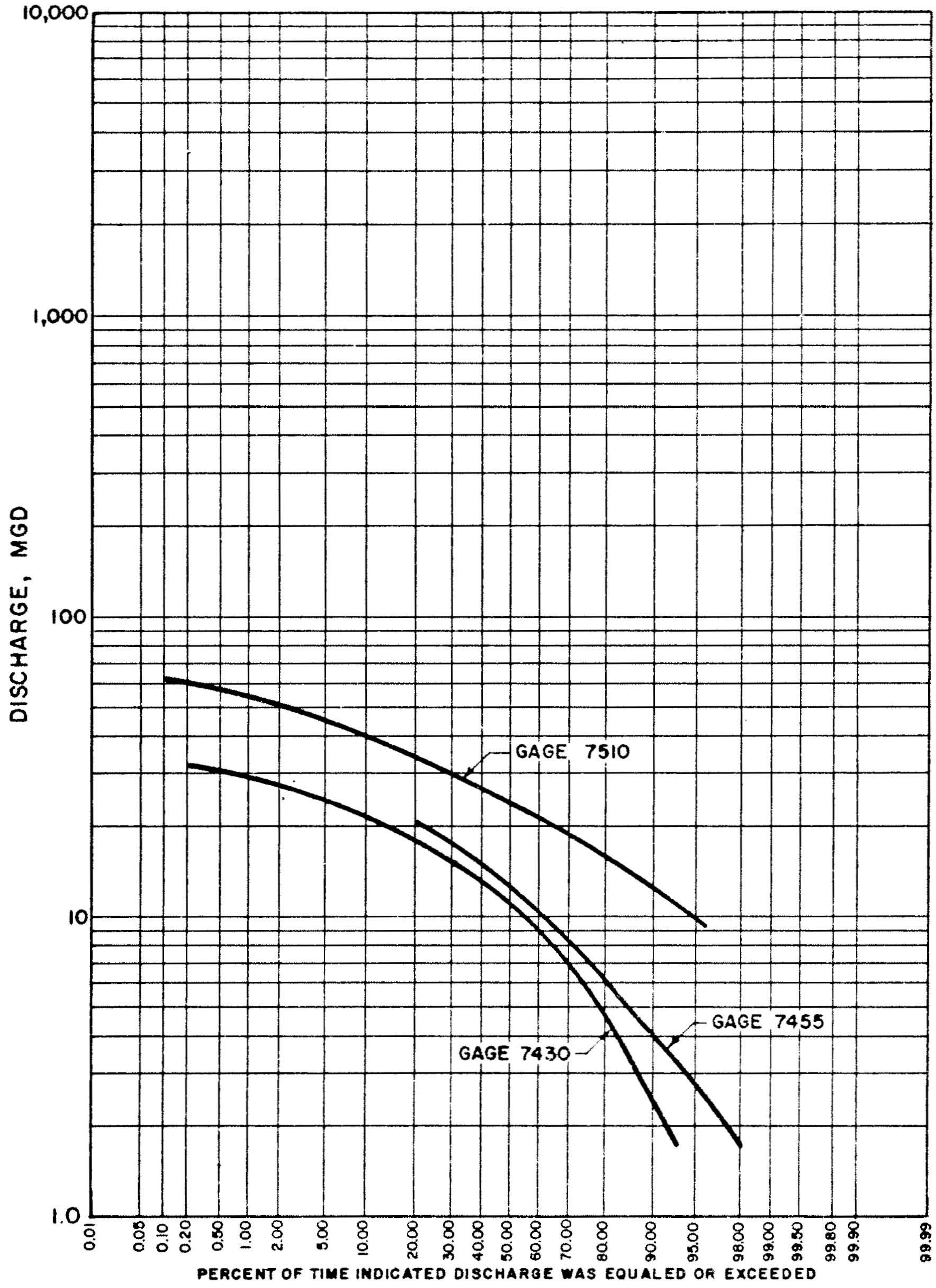
The nature of stream flow in the Awini sector is highly variable, the flow in each stream ranging within a period of a few days from near zero flow to hundreds of mgd and in the entire drainage area from near zero to thousands of mgd. Contributions of streams to the transmission system at any moment depend on the volume of flow already in the system at the intakes; if the tunnel is full, flow from all streams down gradient will be lost. The tunnel capacity and intakes limit the fraction of total natural drainage which could be captured. In dry periods most stream flow is collected except when intakes are clogged, but when the total of all streams is greater than 35 mgd the surplus spills away to the sea.

Instantaneous flows are log-normal distributed and the likely presence of other non-linearities in the set of flow characteristics means that contribution from particular streams or groups of streams are not a simple linear proportion of total flow. Except at low flow much of the total drainage basin is non-contributory to output at Gage 7430, yet the non-contributory streams would fill the tunnel if others were blocked out. An analysis of the natural flow duration curves for each stream, constructed by correlation with the streams to the east of Awini (see Phase II Report), indicate that, were proper flumes installed, for 60% of the time no flow from the streams between Gage 7430 and Ohiahuea could enter the tunnel because the total of the flows of Ohiahuea, Nakooko, Kamoloumi, Waiapuka, and Waikola would exceed 35 mgd. That this is not contemporarily the actual situation, however, is the result of the flume across Oniu gulch having been replaced by two 18 inch pipes. Thus very little water gets into the system from beyond Oniu; most of it is obtained from Honopue westward to the gage.

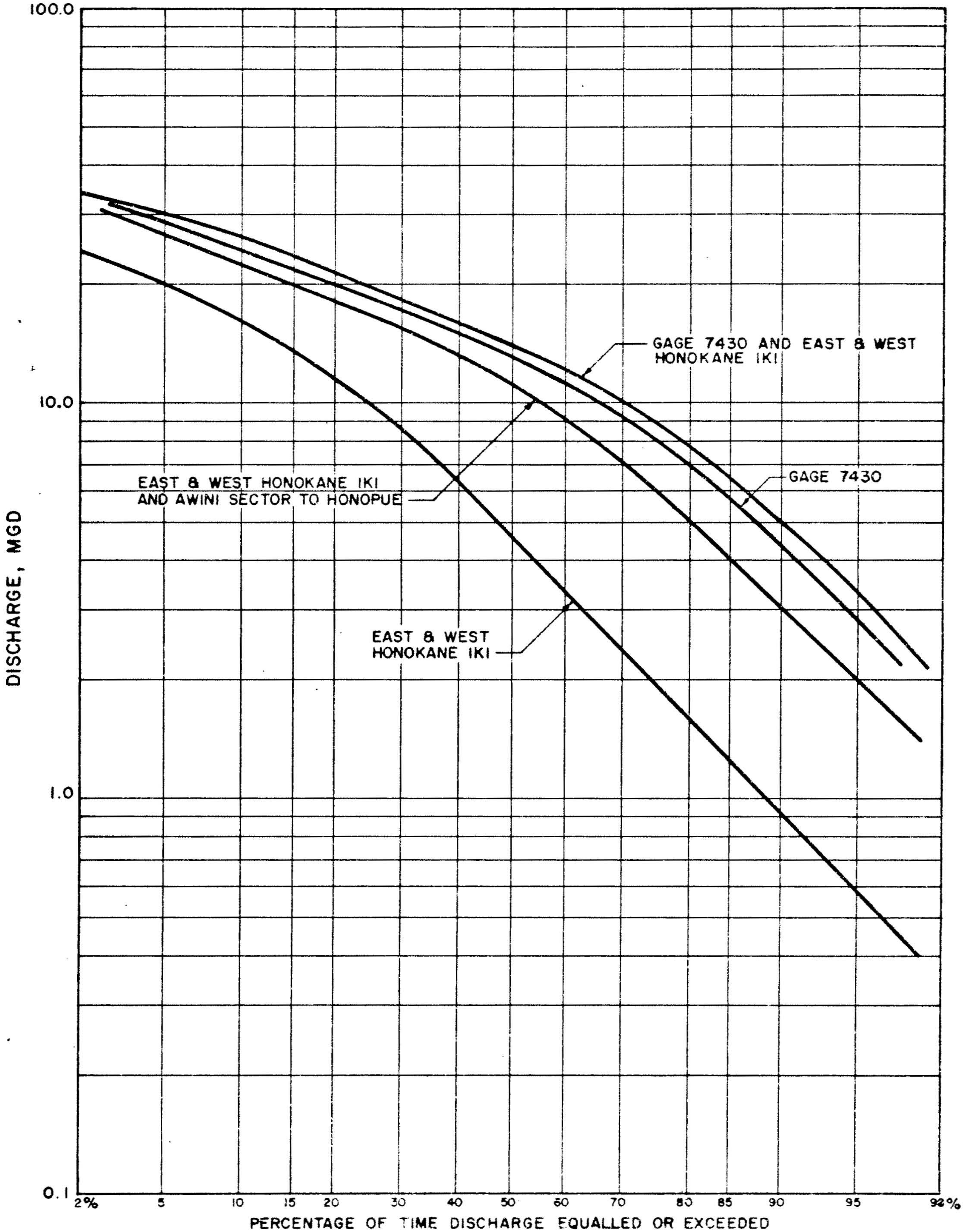
To evaluate the effects of abandoning all or portions of the Awini sector on flows ultimately reaching Gage 7510, synthetic flow duration curves of tunnel transmission were computed using the flow events model and a tunnel capacity of 35 mgd. Synthetic curves were computed for East and West Honokane Iki alone, Gage 7430, Gage 7430 plus East and West Honokane Iki, and the stretch from Honokane Iki to Honopue, including East and West Honokane Iki, Waipahi, the left, second right and first right branch of Honokea, Kailikaula, the left branch of Honopue, and the first right branch of Honopue (a high waterfall). These curves are plotted in figure 7, and in figure 6 for comparison are plotted the actual flow duration curves of Gage 7430 and of Gage 7455, which includes East and West Honokane Iki and 7430. The fits are good, as outlined earlier, with the synthetic curves 1 - 2 mgd higher because optimal intake conditions are assumed.

The synthetic flow duration curves in figure 7 show that if all of the Awini sector were abandoned and only East and West Honokane Iki went into the tunnel the loss in volume would be substantial, but that if the stretch from Honokane Iki to Honopue were kept while Honopue to Wakaloa, the more distant and difficult part of the Awini sector, were abandoned the loss in flow to the discharge to East Honokane Nui would be 2 - 3 mgd at all percentile levels. Table 14 summarizes computed data for the 30, 50, 70 and 90 percentiles for various synthetic flow duration combinations and for the actual flow duration curves at Gage 7430 and Gage 7455.

FIGURE 6




AWINI - KOHALA SYSTEM: FLOW - DURATION CURVES




AWINI SYSTEM: SYNTHETIC FLOW-DURATION CURVES

Table 14

Percentile flows (mgd) for portions of and all of the Awini sector

| | Percentiles | | | |
|---|---|---|---|---|
| Synthetic curves | 30 | 50 | 70 | 90 |
| E. and W. Honokane Iki | 8.8 | 4.5 | 2.3 | 0.9 |
| Gage 7430 | 17 | 14 | 9 | 4.4 |
| Gage 7455: | | | | |
| E. and W. Honokane Iki plus Gage 7430 | 18 | 14 | 10 | 5.0 |
| E. and W. Honokane Iki to Honopue | 16 | 11 | 7 | 3.0 |
| Actual curves | | | | |
| Gage 7430 | 16 | 12 | 7 | 2.4 |
| Gage 7455 | 17 | 13 | 8 | 4.0 |

Figure 8 gives the actual flow duration curve at Gage 7510 and the synthetic flow duration curve, computed from the flow events model, of the East and West Honokane Nui contributions to Kohala Ditch with the Awini sector and Honokane Iki inputs blocked out. This model presumes total abandonment of the collection and transmission system to the east of East Honokane Nui canyon. Comparisons at the 30, 50, 70 and 90 percentiles are as follows:

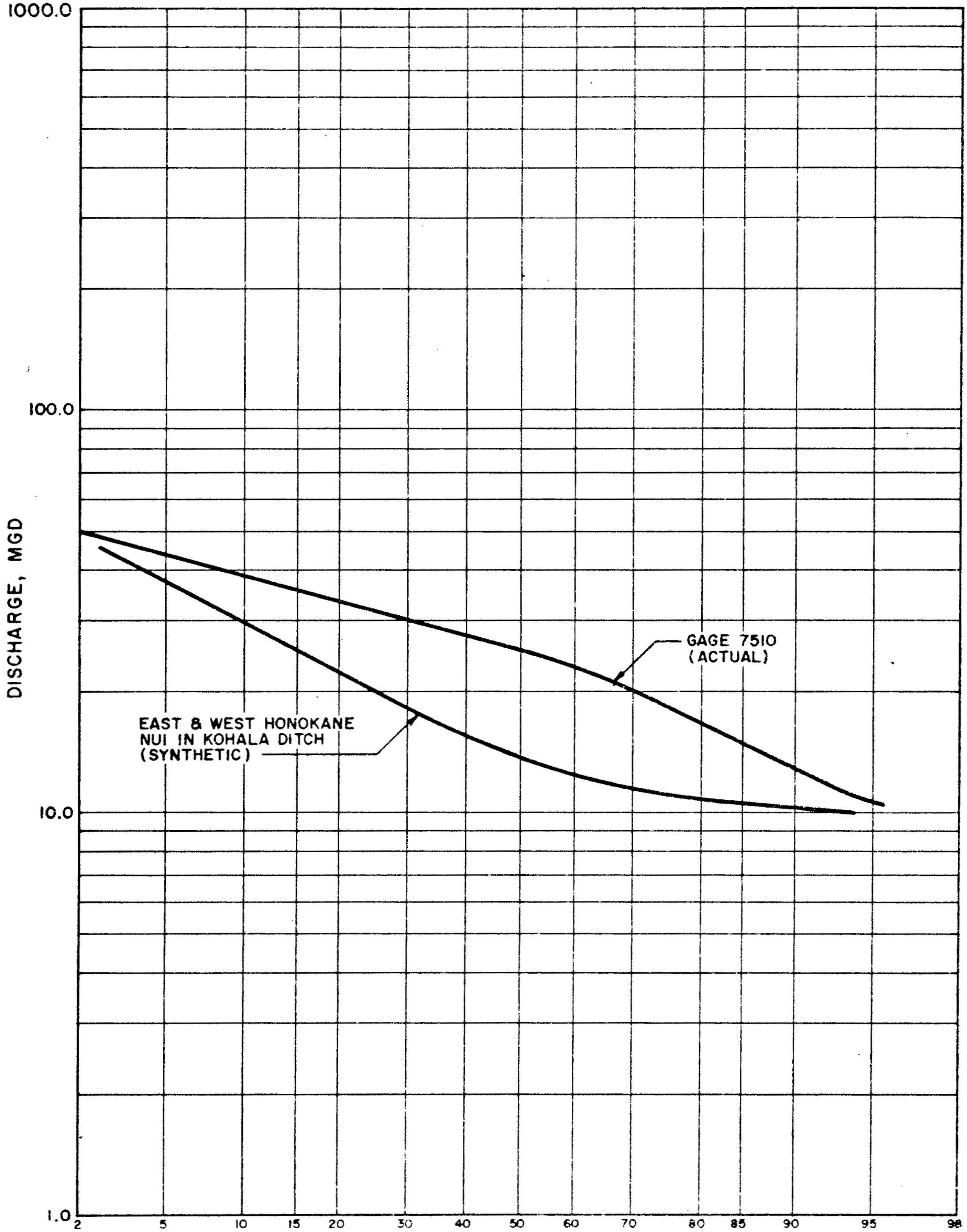
Table 15

| | Percentile. Flows in mgd. | | | |
|---|---|---|---|---|
| | 30 | 50 | 70 | 90 |
| Gage 7510 (actual) | 30 | 26 | 20 | 13 |
| E. and W. Honokane Nui (synthetic) | 18 | 14 | 12 | 10 |
| Difference | 12 | 12 | 8 | 3 |

At low flows the absolute loss would be about 25%, but this is when water, no matter how small a quantity, is most needed. In the mid-percentile ranges the loss would be about 12 mgd, while at the very low percentile ranges very little loss would occur.

Clearly the small volume of water supplied by Awini in dry periods should be evaluated against alternative water sources such as groundwater and water from artificial or high level dike storage. But if Awini were abandoned, for about 60% of the time Gage 7510 would be putting out approximately 10 mgd less than it did during the period between 1928

FIGURE 8




HONOKANE NUI SYSTEM: SYNTHETIC FLOW-DURATION CURVE
GAGE 7510: ACTUAL FLOW-DURATION CURVE

and 1960. The average flow then was 27 mgd; with only East and West Honokane Nui on stream it would be 14 mgd, a loss of 13 mgd. In effect, the additional water from Honokane Nui would only make up about one mgd of the lost supply of Awini and East and West Honokane Iki.

It should be noted that the conclusions given above are derived from correlation and simulation models so that the numerical values presented cannot pretend to be precise. However, they do establish good approximations to flow expectations under different circumstances of collection and transmission.

Koelling Tunnel (U.S.G.S. 36) in East Honokane Nui

The Phase II report described and analyzed data available for Koelling Tunnel, which penetrates high level dike water at the head of East Honokane Nui Canyon. A more refined analysis was subsequently made as a result of which the value of the recession constant was changed from .00075 to .00123 and the initial storage flow from 6.6 mgd to 4.6 mgd.

Although initial storage was completely drained more than 20 years ago, additional high level storage exists between stream level and the tunnel entrance over a vertical distance of 170 feet. Access to the head of the canyon at stream level is very difficult, but the value of a reliable volume of water whose output is controllable may at some time justify a horizontal test and development well. The failure to strike high level water lower down in the canyon with a horizontal boring suggests that saturated dike compartments significantly above stream level are restricted to the upper reaches of the canyon.

## WATER MANAGEMENT AND DEVELOPMENT ALTERNATIVES FOR THE AWINI AND HONOKANE SECTIONS OF THE KOHALA DITCH

Water sources in Honokane Nui Valley are especially critical to the Kohala Ditch supply, particularly during periods of deficient rainfall. In conjunction with the exploration program and search for adequate storage, certain potential sources of water in Honokane and Awini were evaluated for their value as a supply and for construction and operational feasibility. These following evaluations have been made with the purpose of removing doubt as to feasibility and to clearly document basic criteria for analysis.

Following the completion of the Awini field trip in February, much consideration was given to the recommendations of improvements to the existing ditch system. It was evident before the field trip and confirmed by field observations that any construction in the Awini Section would be relatively very costly compared to urban and rural construction. It was felt unrealistic to estimate costs based on high current conventional construction prices. These prices should reflect the high risk factors found here due to safety, weather, and logistics. It should be reiterated that 17 lives have been lost in the construction and maintenance of the ditch. Present construction costs for similar ditch tunnels are in the range of $300 to $500 per lineal foot. This is not to say that construction of improvements are not feasible. It is recommended that the costs of any proposed ditch improvements be initially estimated on the following basis:

1) Where possible, the present reduced organization of the Kohala Ditch Company be reinforced and continue the maintenance and operation as well as improvements and repairs to the existing system. Up to the present, the company has had the benefit of manpower availability from Kohala Corporation sugar plantation when needed for construction and repair of the ditch structures. For the future, it appears that the ditch company would still be better able to operate the system and find manpower from farming operations in the area for its needs. In our findings, utilization of the company's familiarity and accumulated experience with the system, and complemented with technical engineering assistance as necessary from government and private sources, would be the best approach. Concerns over adequate maintenance of the very remote, and inaccessible, not to mention dangerous, intake-tunnel-ditch system by an untried operator would be lessened. There are also the OSHA act requirements which need to be complied with.

With the phasing out of sugar cultivation, there is a question of any increased water demand in the initial stages of conversion to other crops or activities. Consequently, there is not only a lead time for improvements to the ditch system but also a question of need or extent of improvements currently. (However, there is a vital current need for further exploring and reporting findings of the possible maximum capability. This is for furnishing irrigation water especially during drought periods and, equally important, for the maximum future agricultural development of North Kohala.)

Costs can be better estimated and capital outlays recommended after the setup of the Kohala Ditch Company for the future is determined. Work to be done can then be evaluated on the basis of whether it is to be performed "in-house" or by contractual basis. On an "in-house" basis, cost of labor, materials and equipment as well as overhead may be calculated after wage schedules, allowances for board and subsistence, etc. are established and made known. Costs of improvements and repairs can then be estimated more closely.

It may be pertinent to relate here that under this phase of consultant services, dependence was made heavily of such current conveniences as radio telephones and helicopters for communication and transportation respectively in the exploratory drilling work. Otherwise, this would have had to be accomplished with the use of the few remaining aged mules over the winding trails. While these modern services cost more, there was considerable time-savings as well as improved communication which resulted in overall efficiency.

2) When putting out improvements projects to bid and by contract, the usual procedures govern. However, in addition, it becomes necessary to escort and guide

the interested bidders to the site of the projects.

Depending on the water demand and consequent level of operation and maintenance required, the following recommendations are made:

1) If, due to demand, the Awini Section is not presently needed but may be needed in the future, it is advisable to do the following:

   a) Sluice all the intakes, flumes, and especially the tunnels.

   b) Close up the intakes, flume inlets, provide drain openings for the flume outlets, and close off all the adits from public access.

   In this manner, the ditch system can be reactivated with the minimum of cost by minimizing the interim damage to the system.

2) If the Awini system is necessary at its present improvement level, it is advisable to:

   a) Sluice all structures as listed above.

   b) Clean out all alluvium and bed load behind the intake dam structures routinely.

3) If the water demand justifies upgrading the Awini system, the following projects should be evaluated in relation to meet the water demand and the level of operation and maintenance that goes with it.

   a) Replace the Oniu pipe flumes with 60" diameter half section metal flumes.

   b) Reconstruct adits or close off adits to eliminate them as constraints to the capacity of the tunnels.

c) Enlarge intake openings where its existing capacity does not catch the level of flow desired. Also, the intake location and design should consider reducing the level of maintenance by making the structure self-cleaning of debris and reduce the bedload build-up at the entrance.

d) Where feasible construct sediment traps upstream where bedrock and area is available relatively close to intake structure. In this way alluvium and debris will be minimized at the intakes.

e) Improve safety of trails to intake and flumes where possible. Providing a handrail steel cable anchored to the canyon walls would be a marked improvement.

f) Provide permanent radio communication systems if safety requirements or ditch and trail operations necessitate it.

Awini Penstock

The Awini penstock system, which includes pumphouses containing two centrifugal pumps (Pump No. 1 and No. 2), together with tunnels, ditches, intakes and pipelines that were initially constructed in 1918 and 1919 to pick up additional water below the main Kohala ditch. The penstock utilized the water flow and energy head from the Awini section by Kohala intake dam to recover Honokane Nui stream water below the Kohala intake dam. This system was continually upgraded over the years. In 1967, Kohala Corporation replaced the Pump No. 1 with a new Worthington Model CT-5 pump modified as follows (See Bowles, Kohala Phase 1 Report):

Pump suction flow,
1850 GPM Turbine flow,
800 GPM Total pump head
115 Ft. Turbine supply pressure
300 p.s.i.g.
Pump speed 2600 R.P.M.

This system was abandoned as the Kohala Ditch Company reduced their level of operation and maintenance. From interviews with the Ditch Company personnel, it was learned that the operation required a pump man full time to check the pumps and keep the intakes clear.

The lower Pump (No. 2) operation has long been abandoned. This system would have to be replaced rather than be rehabilitated. Consideration of complete replacement must be weighed with the alternative of developing new water sources.

Pump No. 1, consisting of a relatively new pump should be considered for rehabilitation based on its condition which was visible on field inspection. A preliminary cost estimate to repair the system "in-house" is $10,000, assuming minor repairs to intake and piping systems. The consideration to utilize this existing system should be based on the following:

1) Kohala Ditch Company has to be operated at a higher level in Honokane Nui (East Branch) with enough facilities to operate and maintain so that the cost could be prorated over the numerous facilities and the quantity of water delivered from Honokane Nui would justify such additional costs.

2) No major repairs to the penstock facility were considered. Penstock replacement, estimating roughly, with current construction cost of 6- inch pipe installed at $40 per linear foot, the cost of 1,900 linear feet would be around $76,000.

Hydropower From Sproat Falls

It was decided to consider the feasibility of generating hydropower from the existing falls (referred to as Sproat Falls) located approximately 2,400 feet above Awini Falls and the Kohala main intake. The base of this falls is the location of the exploratory horizontal drill hole.

The flow of the falls was measured by Bowles and Akinaka by the sharp edge V-notch weir method and found to be approximately .25 mgd. This flow has been visually observed to be fairly constant throughout the period of our exploration.

The hydropower model would consist of diverting the water from the falls, the top of which is about 500 feet above the Honokane Nui canyon floor, into a pipe intake at its source. By anchoring a 6-inch pipe penstock to the canyon wall, its energy would be transmitted to the approximate location of the vertical exploratory test hole along the opposite canyon wall and power a pump which would discharge into the stream thence the main Kohala ditch intake. The power might be used directly to operate a hydraulic centrifugal pump or converted to electricity to operate a deep well turbine or submersible pump. Approximately 20 horsepower would be available on utilizing this energy source. The tailwater would discharge back in the stream for diversion down the valley.

Based on the specific capacity of the vertical exploration hole, a hydraulic centrifugal pump does not appear feasible as the drawdown would be in excess of 20 feet at 100 gpm. In order to be a significant overall water contribution, the pumping rate of a deep well should be 700 gpm (1 mgd) or greater. About 60 Bhp would be needed to pump 700 gpm from a well in the high level aquifer at this location. Because only 20 hp might be generated from Sproat Falls, it would not be feasible to use the potential energy for pumping.

The most effective use of the Sproat Falls hydropower would appear to be for supporting an operations camp or control systems for pumping operations in the area. A rough estimate for installing a penstock would be $60,000.

Feasibility of Pumped Wells

Vertical exploration during Phase III has conclusively indicated the presence of high level groundwater lying beneath the stream in the vicinity of Sproat Falls as reported earlier. Analysis of stream flow probabilities during the Phase II work and as contained in this report clearly demonstrates the need for high level storage especially in Honokane Nui. The major effort of the Kohala Water Plan has been to determine the most feasible means of developing additional water for augmenting dry weather flows of the Kohala ditch.

Pumping water from storage is one means of gaining flow stability in the ditch. Development of major groundwater storage in Honokane could ultimately result in a reduction or possibly eliminate the need of operating and maintaining the Awini section. At present the demand for irrigation water in Kohala proper does not warrant anything more than a maintenance of existing ditch facilities. As demand approaches the useage levels similar to those of the full sugar operation, the need for stable dry weather flow will recur. Development of about 1000 mg of stored water would markedly improve the reliability of low flows (see section on storage analysis). Low lift pumping in Honokane could be used to develop such storage, however, an external energy source would be needed.

The exploration well was drilled and tested in order to determine the feasibility of pumped wells in Honokane. Figure B is a graphic analysis of the aquifer test performed on the test well. Based on this data, performance of a hypothetical well was evaluated to determine the potential

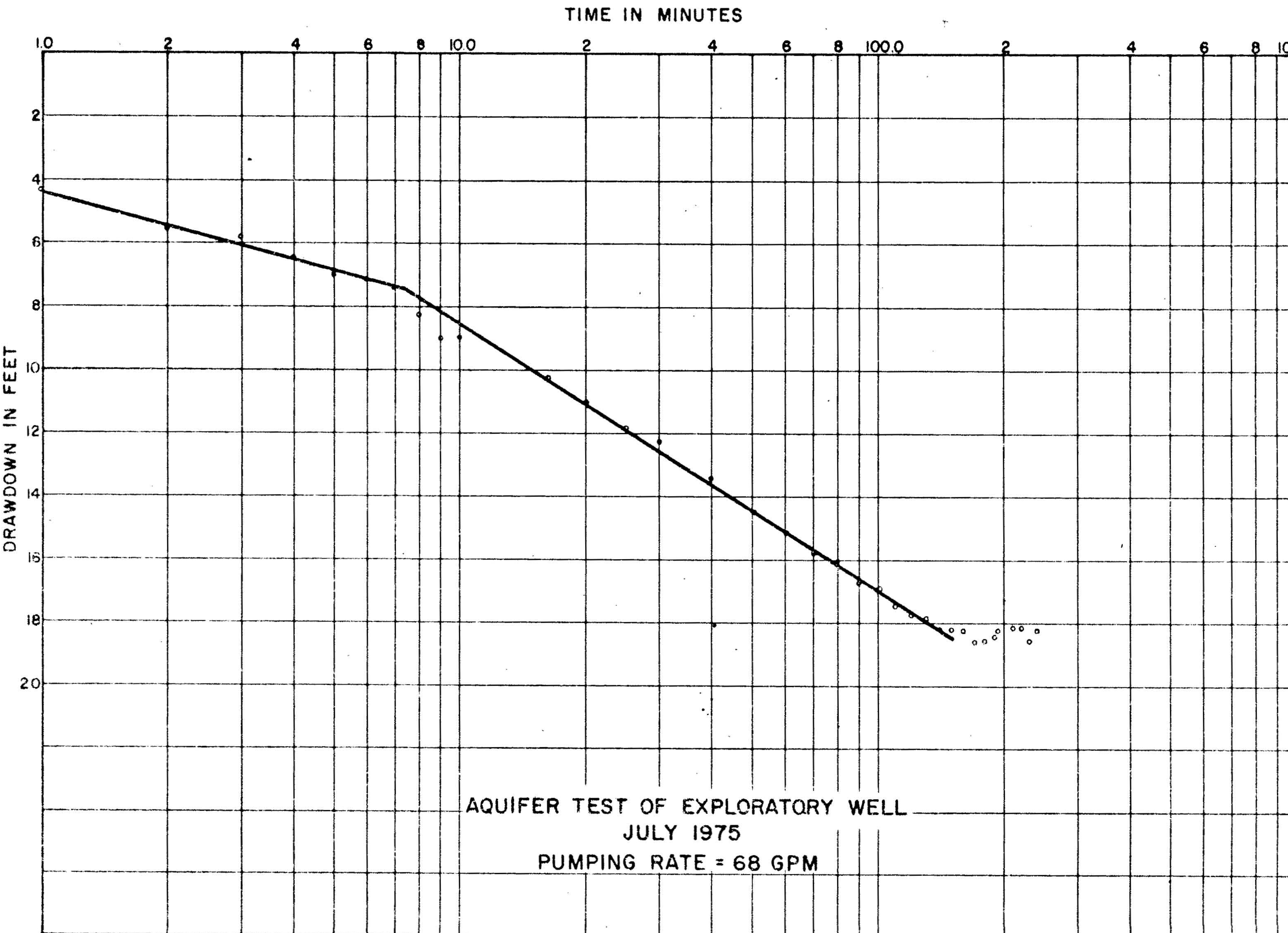

TIME IN MINUTES
1.0
2
4
6
8
10.0
2
4
6
8
100.0
2
4
6
8
1000.0
DRAWDOWN IN FEET
2
4
6
8
10
12
14
16
18
20
AQUIFER TEST OF EXPLORATORY WELL
JULY 1975
PUMPING RATE = 68 GPM

FIGURE B

development. Shown below is a capital and operating cost analysis for a well of this type with assumed yield and dimensions:

Capital Improvement Cost

| | | |
|---|---|---|
| 1) | Deepwell 12" casing; and appurtenances: | $30,000 |
| 2) | Deepwell pump (700 gpm @210 TDH, 60 BHP, 200' setting, 8" oil lube) | 20,000 |
| 3) | Right Angle Drive | 4,000 |
| 4) | Diesel Engine (GM 3061A 75 HP) continuous rating selected for this study) | 6,000 |
| 5) | Concrete and miscellaneous piping | 2,000 |
| 6) | Fuel storage tank (1000 gallon capacity, sufficient for 1 week continuous operation) | 3,000 |
| 7) | Helicopter transportation (assume 40 hours @ $250.00/hr. | 10,000 |
| | | $75,000 |

Annual Operating Cost (Operate 4 months/year)

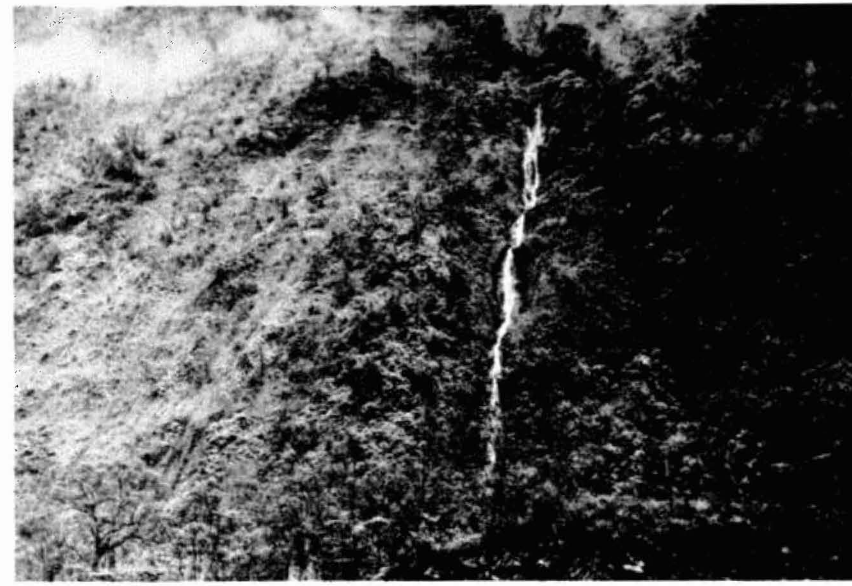
| | | |
|---|---|---|
| 1) | Pump Personnel @ $700.00/mo. for 12 months | 8,400 |
| 2) | Fuel $600/wk x 16 weeks | 9,600 |
| 3) | Lubricants | 300 |
| 4) | Repair parts | 100 |
| 5) | Helicopter time (2½ hrs/wk x 16)@ $250/hr | 10,000 |
| | $28,400/120 MG=$237/MG | $28,400 |

To achieve access to storage of 1000 mg, about 10 wells would be needed. With the logistic problems and the size of Honokane valley, particularly above the ditch intake, this would be a difficult achievement. Wells at or just makai of the intake dam are feasible and pumping lifts of 500 feet or more might be expected. While the present cost of pumping water to the ditch appears to be prohibitive, Honokane Nui is the only valley north of Waimanu to cut deeply into the dike system of the Kohala Mountain. For this reason, Honokane Nui is a major existing and potential source of water for North Kohala. Any water developed in Honokane will arrive in the agricultural area at an elevation of 1000 feet. This provides a great potential for agriculture in the district.

Test results of the vertical well indicate that the base flow, rising in upper Honokane, would probably enter the aquifer by downward leakage from the stream resulting in a smaller net gain in low flow to the ditch. From this data and the analysis of the flows from Awini, it is strongly indicated that the most promising storage solution for the Kohala ditch lies in drilling or tunnelling for high level gravity flow farther up the valley.

Test drilling by Kohala Plantation and the recent horizontal and vertical exploration has virtually eliminated the prospects of gravity type development in close proximity to the Kohala dam and intake. Exploration farther up the valley is needed. Such exploration should be limited to horizontal drilling into or in search of suitable dike structures storing water for gravity release. It is noted here that the original storage of the Koelling tunnel was in excess of 1000 mg (see Phase II report), thus such storage can be obtained in Honokane. Unfortunately, Koelling tunnel is probably not situated properly to be operated for this purpose.

AWINI FALLS AND MAIN KOHALA
DITCH INTAKE – HONOKANE-NUI
(EAST BRANCH)



"SPROAT FALLS"

MEASURING OF "SPROAT FALLS"
BY SHARP EDGE V-NOTCH WEIR METHOD

## REFERENCES


1. Bowles, S. P., Mink, J. K., Akinaka & Associates, Ltd., and May, C. S., 1974, Kohala Water Resources Management and Development Plan, Phase II.

2. Fiering, M. B., and Jackson, B. B., 1971, Synthetic Stream Flows: Water Resources Monograph No. 1, American Geophysical Union.

3. State of Hawaii, 1965, Flow Characteristics of Selected Streams in Hawaii: Division of Water and Land Development Report R27.

4. Stearns, H. T., and Macdonald, G. A., 1946, Geology and Groundwater Resources of the Island of Hawaii: Territory of Hawaii, Division of Hydrography, Bull. 9.

5. United States Geological Survey, 1961, Compilation of Records of Surface Waters of Hawaii through June, 1950: Water Supply Paper 1319.

6. United States Geological Survey, 1964, Compilation of Records of Surface Waters of Hawaii, July 1950 to June 1960: Water Supply Paper 1739.

7. United States Geological Survey, 1971, Surface Water Supply of the United States, 1960-65. Part 16 Hawaii and Other Pacific Areas: Water Supply Paper 1739.